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Cover illustration: Thin sections of several different habits of barite. Photographs: Jane Clarke.

Botryoidal barite Mag 538; ppl.	Acicular barite Mag 549; xpl.	Poikilotopic barite Mag 530; xpl.
Bladed barite (white) Mag 580; ppl.	Botryoidal barite Mag 538; xpl	Spherulitic barite Mag 584; xpl.
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The long history of geological studies in Dorset confirms its World Heritage Coast status

Hugh S Torrens, Professer Emeritus, Earth Sciences, Keele University

Abstract

This lecture will review the long history of Dorset's geological involvements, from the foundation of the Royal Society in the 1660s up to its designation as one worthy of WH status late in 2001. An attempt will be made to interweave the roles of academic and industrial geology, since the latter aspect is all too often forgotten. The history of 'industrial geologists' in Dorset proves quite remarkable. These range from the Vicar of Long Burton in the north, one William Sharpe, who published a philanthropic *Treatise upon Coal Mines* in 1769 to Sir John Webb of Canford in the south (died 1797) who wasted an enormous sum (up to £15,000) looking for this same material high up in Tertiary rocks, in what is now called the Poole Formation, near Canford in the 1770s. Final industrial stupidities involve attempts to find coal near Weymouth in the 1870s and the Lyme Regis cement maker, George Haycraft, who was still trying to find this non-existent material (at least in Dorset), to better make his cement, as late as 1901.

Some of the major figures on the more academic front will include John Woodward (died 1728) whose remarkable collections still survive in Cambridge and William Smith, whose pioneering work, across industry and the academy, as a stratigrapher had interesting Dorset dimensions. The work of some of the early members of the Geological Society of London (1807), like Henry de la Beche, William Buckland and William Conybeare, often built on the discoveries of that remarkable woman Mary Anning (1799-1847), who brought the palaeontological treasures of Lyme Regis to international attention. Later in Victorian times, Dorset produced, or gave homes to, others of real interest, like the geologist who first advised on the Channel Tunnel, or the natural history dealer from whose Weymouth base, the world's museums became filled with materials from all over the world. Others include a pioneer in the field of what we today call geophysics, and the two Buckmans, father and son, who either helped found the Dorset Natural History Society or showed with what precision fossils could allow the chronology of the geological record to be investigated. Perhaps the most intriguing was that world-significant figure, the palaeobotanist Marie Stopes, whose much-planned child was conceived in the old lighthouse on Portland and whose last scientific paper (in the 1950s) was also written there, with the man who revealed that Piltdown man was a forgery. Dorset has produced, or given homes to, a wonderful tapestry of geological discoverers who certainly deserve to be more widely known.

Introduction

My lecture has several purposes:

1) To explore the profile of geology in Dorset which has been so much advanced by the designation on 13 December 2001 of its coast as "The Jurassic Coast" or "The Dorset and East Devon World Heritage Site", the first such natural site in England (Brunsden 2003).

2) To point out the economic significance of a knowledge of geology, either throughout its complex past, or at present and progressively more in future.

3) To point out, despite this, how ignorant people still are about general geological matters, like *The Times* writer who could announce in January 1993 how it was proposed to honour The Few (of the Battle of Britain) by a new statue on the top of the White Cliffs of Dover (more geology) "carved out of some light blue Dorset granite". Such ignorance may also explain the 'wrong' stone being used for the British Museum's wonderful new, but not Dorset-sourced, Courtyard (*Daily Telegraph* 25 August 2000, 4). This had come from the Middle Jurassic (Bathonian) of the Yonne (Anstrude Roche Clair) in France instead of the Upper Jurassic (Portlandian) stone which was intended.

4) To point out how many significant geologists have been native to, or been based in, Dorset.

As an administrative political unit Dorset is not easily defined geologically. But, however now defined, this county contains representatives of most rocks deposited from a period circa 200 million years ago right up to those of 'the present'. It has the inestimable advantage of a wonderful seacoast which has yielded (and continues to yield) wonderful outcrops and their contents for study. But it has also had the major geological disadvantage of never having suffered any major 'industrial revolution'. Thus it still has few railways (despite the survival there of the remains of one of the earliest of these in England), no canals and few major mines (despite considerable attempts at creating both of these).

Learned Societies

The role of learned societies in the development of English geology has been crucial. The Royal Society of London from 1662 was inspired by the work of one Joshua Childrey (1623-1670) who was the author of one of the then most influential books on natural knowledge, *Britannia Baconica: or the natural rarities of England, Scotland and Wales* (London: for the author, 1661 - with a French edition, 1667). This had only two and a half pages

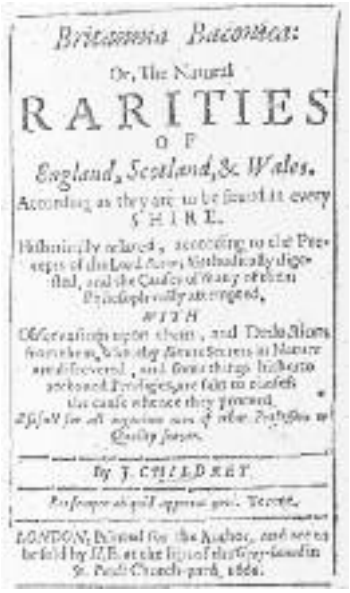
Britannia Baconica:
Or, The Natural
RARITIES
OF
England, Scotland, & Wales.
By J. CHILDREY.
LONDON, Printed for the Author, and are to be sold by H.B. at the sign of the Grey-hound in St. Pauls Church-yard, 1661.

Figure 1. Title page of the book by Joshua Childrey 1623-1670.

devoted to Dorset. Childrey was born at Rochester in Kent and after Oxford University, in 1660 he was appointed chaplain to Henry Somerset, Lord Herbert (1629-1700) who lived at Badminton, Gloucestershire, which explains why his *Britannia* has twelve and a half pages on Gloucestershire. Smith (1942) has examined Childrey's observations on minerals, rocks and fossils here and concluded that he was among the first in this country to refer repeatedly to fossils.

In 1664 Childrey was appointed rector of Upway, in Dorset, and so was now able to investigate this county in much more detail. We know something of this work from his letters in 1669 and 1670 to Henry Oldenburg (?1615-1677) (Hall & Hall 1968-1969). In one of these dated 12 July 1669 (Hall & Hall 1969, 107-10) Childrey writes that he had entered all the "philosophical matters" with which he had met in his reading into many manuscript books and these, with two larger folio volumes containing his notes on the chronology and geography of nature, he intended to bequeath to the Royal Society on his death. This happened on 26 August 1670 at Upway (Wood 1721, vol. 2, 468), where he is buried in the chancel. But his manuscript failed to reach that Society and it would be most valuable to discover if they have survived.

In 1673 we have the first notice of that palaeontological gem Lyme Regis. The botanist John Ray (1627-1705) travelled much round both Britain and on the continent. Raven (1950) records how in 1662 Ray undertook "the journey which was both from the personal and from the scientific standpoint a most important event in his life". Details are sparse but this tour which started from Cambridge, went first across to Wales, then south via Bath to Land's End then east via Exeter on to Sherborne. Raven does not mention any specific detour to Lyme. But Ray does record the place in his later discussion of the fossils up till then found in Britain. Here Ray notes the six "places in England which afford plenty of these petrified shells" and then gives his own additions, noting "beside which places, myself and friends have seen and gather'd of them at Lyme in Dorsetshire" (Ray 1673, 115; 1728, 97). It seems certain that his Lyme visit was during this 1662 tour.

The Eighteenth Century

The long influence of the Dorset coastline, and more marginally that of the same Royal Society, continues visible in the next significant contributor to our understanding of Dorset's geology. This was one made in 1715 by a Weymouth customs officer cum mariner called William Hobbs (fl. 1709-fl. 1715). In July 1973 I saw his unknown MS Treatise for sale in a London bookseller's catalogue and persuaded the British Museum (Nat. Hist.), as it then was, to purchase it (Dawson's *Catalogue* 240, item 220, 1973). This MS was beautifully edited by the late Roy Porter and issued in 1981. Roy discusses both what little is known about its author and what his Treatise reveals of Hobbs' knowledge of geology.

At a time when most accepted the idea that the Biblical Deluge had provided the source for all sediments, Hobbs instead realised that:

1) all the fossils commonly found in those Dorset rocks with which he was familiar were the remains of once real animals
2) these animals had not been placed there by any Deluge but had been embedded in rocks which had formed on the sea floor
3) these rocks had later been raised up by 'pulsations from the centre of the earth' and
4) it was these same pulses which had also caused the tides - in which he had an all-embracing interest as a mariner. His view was against that of his contemporary Isaac Newton (1642-1727) who correctly believed that lunar influences were the cause of tides.

Hobbs clearly had an alchemical view of the Earth, viewing it as analogous to an organism with 'the pulsations' being its heart beats etc. He shows a clear interest in his local area as befits a mariner and he must have made his own collection of Dorset fossils (but which are now lost).

Figure 2. Dr John Woodward (?1667-1728).

The next contributor to Dorset's geological exploration was that complex character Dr John Woodward (?1667-1728), proto-geological-museum-builder. The discovery of his Derbyshire father's will has revealed a lot more of his previously unknown origins (Torrens 2003a, 81-2). Between 1688 and 1690 he became an omnivorous gatherer of all materials from the Earth, whether fossil, mineral or mere sediment. These were carefully catalogued, and as required in his will issued in a posthumous volume (Woodward 1728-9). Woodward's pioneering collecting methods are also known (Eyles 1973) but their geographical extent has been much less investigated. So the man deserves careful study, especially now some of his long-lost travel journals are safely in public hands (Simon Taylor, *Catalogue 9*, item 208, 1997 now in Cambridge University Library). These discuss his "journeys into Cornwall or Western Fossils" circa 1720, while another records his "Return from Bath in 1722". These may disclose how much time Woodward actually spent in Dorset. The catalogue of his still surviving collections (at the Sedgwick museum, Cambridge) shows that a large number of Dorset localities are represented in it; including Bridport, Henstridge, Lulworth, Lyme Regis, Melbury Abbas, Poole, Portland, Purbeck, Radipole, Shaftesbury and Weymouth. One of his large Portland ammonites (Woodward 1728-9, II, 28) was given him by Mr Christopher Wren (1632-1723) who, with Robert Hooke much worked there in choosing building stone with which to rebuild London after the Great Fire. But that Woodward himself did considerable field work is demonstrated by his note on a fossil echinoid he had found near Beer in Devon: "this was the first sign of [any fossil] impression or shell

I met with from the Lands-End to this place; I not finding the least Vestigium of any Fossil shell in all Cornwall" (Woodward 1728-9, vol. 2, 49).

Some of Woodward's most interesting Dorset specimens derive from an extraordinary, at least 80 feet deep, attempt in 1690 to find coal in the country around Shaftesbury. These include a vertebra of what was later recognised as a pliosaur and a sample of claystone which Woodward recorded had been found there with sea-shells (Torrens 2002, III, 235). This attempt helps us to put Dorset and the coming national 'industrial revolution' into some real context. Rev. William Sharpe's (1724-1783) work in Dorset does this to an even greater extent.

Sharpe was born in 1724 at Houghton-le-Spring, in the heart of the Durham coalfield where a local agent for the newly developed Newcomen steam engines had been appointed that same year. In 1743 Sharpe entered Oxford University, where in 1746 he attended James Bradley's lectures. These introduced him to the rudiments of what were then known of optics, mechanics, astronomy and hydrostatics, but not as yet any geology, which did not yet exist as a basic science. He graduated in 1749 and became a curate first in Essex then in Devon. In 1760 he was appointed schoolmaster at Sherborne School in North Dorset and then vicar of nearby Long Burton parish in 1763.

Here he found his rustic parishioners suffering from a high incidence of what he called 'ague'. The incidence of this ailment was eight times higher than he had known in Durham. This was caused by a complete lack of available domestic heating in Dorset, which had been supplied in Durham by cheap coal. The later fine Dorset historian George Roberts (1803-1860) noted in 1856 how long the southern populations remained ignorant of the possible uses of mineral coal, even in domestic use (Roberts 1856, 345-357). For this reason Sharpe found his Dorset parishioners spending too much time in public houses, simply because it was warm there in winter, unlike their homes. The poet William Wordsworth was to write accurately in his 1798 poem Goody Blake:

This woman dwelt in Dorsetshire
Her hut was on a cold hill-side,
And in that country coals are dear,
For they come far by wind and tide
(Wordsworth 1798, 87).

Sharpe saw that something needed to be done! Local coal was the solution.

Today it may seem merely amusing that this idea was even considered. But then, in the mid-eighteenth century, they had no way to prospect for coal. Its geological distribution was simply unknown. So Sharpe set out to try to remedy this deficiency and in 1769 published his *Treatise upon Coal Mines* (Sharpe 1769). His motive was philanthropic, since he dedicated any profits the book might make to his parishioners. The title of his book notes there were 'indications of coal'. These he listed as:

1) Any type of rock like that known to occur in coal-mines, especially Blue Clay or Ironstone, although he did acknowledge that NOT all coal was everywhere overlain by the same type of rock.

2) Any coal outcropping close by.

3) Any springs of "a vitriolic hue".

Finally, as a sort of sod's law, he noted that

4) the worst coal always lay uppermost (as it was the most weathered).

This last tragically gave even the most slight 'indication' of the presence of coal a reliability it did not deserve.

With this advice the many attempts made, even in never-properly-industrialised Dorset can be explained (Torrens 1975). The extent of these, now clearly misinformed, searches is best revealed by the *Appendix* which Sharpe published in 1770. This deals only with those attempts to find coal known to him as having been undertaken within a few miles' radius of Sherborne between 1700 and 1770. This publication introduces a new problem, as no copy of this *Appendix* is known to survive. But a single copy of a second edition reprinted in the year 1791 does survive (in the Bodleian Library) to solve our problem. This was also again reprinted in Sherborne in that same year (Sharpe 1791).

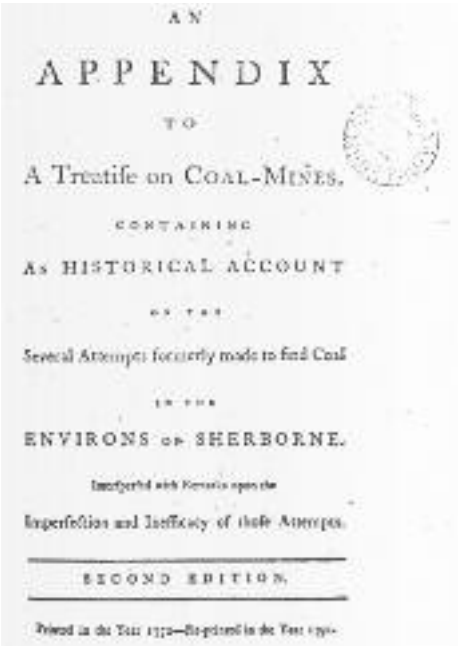
AN
APPENDIX
TO
A Treatise on COAL-MINES.
CONTAINING
An HISTORICAL ACCOUNT
OF THE
Several Attempts formerly made to find Coal
IN THE
ENVIRONS of SHERBORNE.
Interspersed with Remarks upon the
Imperfection and Inefficacy of those Attempts.
SECOND EDITION.

Figure 3. Title page of an appendix by Sharpe (1724-1783).

Probably in 1770, the same year as Sharpe's lost *Appendix* appeared, the Scot James Hutton (1727-1797), so-called 'father of modern geology' visited Dorset. In a letter to John Strange (1732-1799) Hutton noted the distribution of the Chalk in Britain and Ireland and how he had "traveled upon the top of this ridge [of indurated Chalk] from Corf Castle almost to Weymouth" (Eyles & Eyles 1951, 324).

To prove that Sharpe was not so misguided in then trying to find coal in North Dorset we see the same problem being explored in South Dorset, just before Sharpe's book appeared. In 1768 Sir John Webb (c.1740-1797), F.R.S. 1764, the Roman Catholic baronet who owned Canford (as well as property at Odstock in Wiltshire and Hatherop in Gloucestershire) decided to employ a coal prospector on his Canford estates. Here irregular beds of lignite do occur in what were later called the Bournemouth Freshwater Beds (and are now part of the Poole Formation).

Webb chose the best expertise available in coal mining and employed the North of England coal viewer John Barnes (1732-*c.*1781), one of the most respected figures then operating, in far-away Newcastle-upon-Tyne. In 1768 Barnes duly reported on his

survey of Webb's Canford estates (Barnes 1768). He especially noted a 22-inch-thick "seam" of "coal" which he had found at Rockley Point, near Hamworthy. This encouraged Webb to bore many borings, some of which reached The Chalk, to uncover supposed thicker seams thought to lie below in an attempt to turn Poole, with its fine harbour, into a new Bristol.

James Stephen (1733-1779), a "fairly prosperous merchant in London", had “unluckily while at Poole made a great impression upon Sir John Webbe [who] had taken up a grand scheme for developing his property at Hamworthy close to Poole. Stephen, it seems had discovered that there were not only brick earth and pipeclay but mineral springs and coal under the barren soil” [It seems as if Barnes' part in all this was by now unknown]. “A town was to be built; a trade started with London; Sir John's timber was to be turned into ships; a colliery was to be opened - and in short, a second Bristol was to arise in Dorsetshire. Sir John was to supply the funds, and Stephen's energy and ability marked him out as the heaven-sent manager. Stephen accepted the proposals, gave up his London business, and set to work with energy. Coal was found, it is said, 'though of too sulphureous a kind for use;' but deeper diggings would, no doubt, lay bare a superior seam. After a year or two, however affairs began to look black”; Sir John Webbe became cool and then fell out with his manager; and the result was that, about 1769, James Stephen found himself confined for debt in the King's Bench prison (Stephen 1895, 4).

This 'coal' was not coal but lignite which does not

a) occur in seams and

b) would not have been fit for any such use.

Worse, superior seams did not lie below. The whole enterprise is a fascinating, and badly recorded, episode in Dorset's non-industrialised history.

One outcome is that this enterprise was later noted by a close friend (Rev. Joseph Townsend 1739-1816) of the one man (William Smith 1769-1839) who had by then uncovered the stratigraphic distribution of coal in Britain. In 1813 Townsend noted how "the most wild and expensive trial for coal I ever heard of, was, if I am rightly informed by Sir John Webb, on Canford-heath, near Poole in Dorsetshire where he bored two hundred and eighty feet in[to] chalk, and spent as the engineer assured me, near fifteen thousand pounds without the possibility of attaining the object of his pursuit" (Townsend 1813, 428).

This is not far off one million pounds in today's money!

William Sharpe's lost coal prospecting *Appendix* was reprinted twice in 1791, over 20 years after it had been first published, as we have seen. The reason was that a new outbreak of 'coal hunting mania' had now overtaken North Dorset, Hampshire and Devon in that year (Torrens 2002, III, 235). As far as activities in Dorset were concerned, a new Coal Association was then formed in Shaftesbury, by 20 local men, who were all misled by the same simple lithological similarity between the black clays found there (now placed in the Kimmeridge Clay of the Upper Jurassic) with those which they wrongly took to be real Coal Measure clays, as seen in North Somerset. They were still being misled by such lithological similarity (which had been one of Sharpe's earlier 'indications of coal').

The Nineteenth Century

a) William Smith

Figure 4. William Smith (1769-1839).

It was not until what Hugh Miller (1802-1856) later called "the stratigraphic key" became available that this confusion could be overcome (Torrens 2003b). This key was provided by the English mineral surveyor William Smith (1769-1839) from 1797. The twentyfourth of March 1805 proved the 'red letter day' in the history of mineral prospecting in Britain. Smith then visited the village of South Brewham near Bruton, only a few miles north of the then Dorset/Somerset border (Torrens 2001, 72). He then saw a deep mine shaft being dug here, in similarly misleading black clays, and now known to belong to the Oxford Clay. On the basis of fossils he found thrown out of this shaft from a depth of 120 feet, Smith was able to tell those hunting coal here that they were wasting their time. This was simply because they were hunting much too high up in the stratigraphic column again in Upper Jurassic clays which lay way above any Coal Measure clays. They had been confused by lithological similarity. The fossils proved the presence of the Kellaways Stone and so the clays above this had to belong to what Smith was then calling the Clunch Clay. Smith's ability to differentiate between black clays of varying stratigraphic horizons was a crucial scientific breakthrough. Britain thereby became the first country in the world whose stratigraphy was known down to the all-important Coal Measures on which Britain's wealth then largely depended. Sadly, despite this, Smith was to share the same fate in 1819 as James Stephen had in 1769, a period in the King's Bench prison in London, for debt. Looking for coal where it was not and solving the problems of its stratigraphic distribution were both expensive and ill-rewarded activities.

Smith was never apparently active as a mineral surveyor in Dorset, for the simple reason that it was still a non-industrialised county (despite the attempts at Canford and Shaftesbury noted above!) In the 1790s around Bath Smith had worked out the (now known to be sequential) Order of Rocks as exposed in North Somerset, where there was then a major coalfield. His first Order in 1797 had extended from the Chalk [now Cretaceous] down to the highly significant Coal Measures [now Carboniferous]. Smith

also showed, largely as a result of the excavations he was then busy superintending on the Somerset Coal Canal between 1795 and 1799, how fossils could be used to identify many of these strata. Since many of these strata, as we have seen, were highly repetitious in lithology this was a crucial advance. The fossils enabled him to separate the many confusingly black clays which occur in Dorset and often throughout Britain, such as the Lower Lias, Oxford [=Clunch], Kimmeridge, Weald Clays etc.

Smith's three main contracts in Dorset that I have been able to uncover concern:

1) His work for the Earls of Ilchester.
This started with Henry Thomas Fox-Strangways (1747-1802), second Earl of Ilchester. On 18 February 1801 Smith signed an agreement to drain some specified lands of the Earl's at Melbury Sampford and Stockwood. He was to be paid up to £250 if this was completed before 1 May 1801 (original agreement in Dorset Record Office). By 15 May Smith had received at least £194 of this. It must have been then that Smith drew the Earl's portrait in pencil. This survives annotated "late Earl of Ilchester about 1800" (OUM).

Smith's visits here duly introduced him to the geology around Melbury. They also explain how both Cornbrash and Greensand fossils are now to be found in his fine fossil collection (now at NHM) from Melbury. Smith's *Stratigraphical System* records (Smith 1817, 34, 62 etc) that his collection contained fossils from both horizons. This may seem paradoxical until one realises that these two rocks are faulted together at Melbury (see sheet 312 one inch to one mile of the Geol. Surv. of G.B.). This demonstrates that Smith had already correctly separated these potentially confusing, since widely separated stratigraphically, deposits there. Smith also (Smith 1817, 53) recorded Coral Rag fossils from nearby Abbotsbury, which was another estate owned by the Ilchester family.

The second Earl's son Henry Stephen later employed Smith to search for coal beneath the [Triassic] unconformity near Compton Dundon in Somerset in 1813-1815. This proved unsuccessful when the Red Ground [Triassic] here proved to be of an immense, impenetrable, thickness (Torrens 2001, 70). Another son of the second Earl, William Thomas Horner (1795-1865) then became a distinguished diplomat and geologist. He was the first to investigate the order of strata around St. Petersburg, in Russia in 1819-1820 (Ager & Pugh 1965), while posted there. His interest was undoubtedly in part due to the influence of Smith's work at his family home.

2) In 1812 Smith advised the Weymouth Corporation on draining the Backwater at Weymouth.
The man involved was Gabriel Tucker Steward (1768-1836) who had been M.P. for Weymouth between 1794 and 1810 and was also a former Mayor. Smith travelled there on 27 July 1812 and worked in "the marshy area of the Back Water to be drained and improved here" before returning to Bath on 30 July (Smith diaries OUM). On 3rd-6th August Smith wrote his Report, which has not apparently survived. Smith was then paid £25 by Steward who was reimbursed by Weymouth Corporation on 5 October 1814. Their minutes record then that Smith had been "employed to survey the Back Water and give his Opinion as to the Practicability of embanking it" (Weymouth Borough Council, Minute Book p. 178, Weymouth Museum).

On 11 January 1814 Smith's diary notes he was now working on some "Weymouth Harbour enclosure" and copying "Weymouth Harbour Report". This must be in connection with work first planned by John Harvey (1758-1829) on building a breakwater in the Portland Roads, at Weymouth to counter possible French invasions, and the new harbour at Cherbourg opened in August 1813. Christopher Idle (1771-1819), the new M.P. for Weymouth, had taken up the idea in 1812-1813 (Lamb 1824). No Weymouth Harbour reports by Smith have again survived, so it is unclear exactly what his involvement was. But Idle was a subscriber to Smith's *Geological Map* of 1815, so they were at least in contact.

3) In April 1816 Smith advised John Gouger (1788-1878) on "surveying the practicality of increasing the supply of water" to his Abbey Silk Mill at Sherborne in North Dorset (Smith Diary OUM).
Views of this property in 1802 and 1853 appear in Gourlay (1971, opp. 240). Smith was paid £17-12-00 on 1 May, unusually promptly. It was probably during this visit that Smith gathered some of the data needed to draw the geological cross-section, "through Dorsetshire and Somersetshire on the Road through Yeovil to Wimbourn Minster" passing through Sherborne, which he issued in 1819 (Smith 1819; Sheppard 1920, 150-152, plate 16, fig 2). This was the only publication by Smith to deal directly with Dorset. It duly noted the "Pipe or Plastic Clay which has been sought for by various trials on Pool Heath, some of which are said to have been experiments for Coal" (see above!) Gouger's younger brother Robert (1802-1846) later played an important part in the colonisation of South Australia and may have taken Smith's ideas with him.

VIEW
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MIDDLESEX;
THE BOARD OF AGRICULTURE,
BY JOHN MIDDLETON, ESQ.
SECOND EDITION.

Figure 5. Title page of the book by John Middleton (1751-1833).

b) John Middleton
Our next pioneer of Dorset geology has, unlike Smith, been completely forgotten. He is John Middleton (1751-1833). He was born at Winston, Durham and trained as a land surveyor and agent. By 1776 he was based at Lambeth, London and while here he purchased a 200 acre, then country, farm at West Barnes, Merton, in

1787 (Jowitt 1987, 23-32). In 1798 he published the first edition of his *View of the Agriculture of Middlesex* with a second edition in 1807 (Middleton 1798, 1807). Donaldson noted of the first edition that "general opinion has ever allowed this report to be the best of all the surveys of English Counties" [of those commissioned by the Board of Agriculture] (Donaldson 1854, 82). Middleton declined to be remunerated for writing this report and in 1800 he also declined the Board's invitation to do a similar *Report on the Agriculture of Surrey*.

In 1798 (p. 74-5) Middleton had noted that Hessleton Farm, about four miles west of Wareham, was let "on lease for 60 years at £140 a year". This is the first reference found to any involvement of his with Dorset. This farm is now known as Hethfelton (GR SY 852883). It had been sold in 1796 to Dr Andrew Bain (died 1827) (Hutchins 1861, 1, 417-419). Bain, who was then based in London, was appointed Physician Extraordinary to HRH the Prince of Wales in 1809. He re-built the mansion house at Hethfelton also illustrated in Hutchins. In 1808 Bain had been awarded the Gold Medal of the London Society of Arts for planting 338,000 forest trees on his Dorset estate. Between 1798 and 1807 he planted over 800,000 trees on 400 acres there (Bain 1808) and in doing so greatly improved the soils there.

Middleton must have been one of those who advised Bain on how best to improve his considerable Dorset estates.

Middleton would have had to investigate geology for his Middlesex Survey, both editions of which have sections on

a) Soil and Surface and

b) Mines and Mineral Strata.

In the first edition he writes "I have not met with any stratified rock-stone... in this county" and adds that "Coals have not yet been discovered in this county nor do I believe sufficient trials have been made to find out whether there are any or not" (Middleton 1798, 26-7). The next occasion on which Middleton went into print on our subject was in 1800 when he repeated his unfounded belief that coal underlay St. Leonard's Forest in Sussex and, more accurately, that coal strata do not always outcrop at the surface except in hilly and mountainous countries.

As a result of his involvement with Bain, Dorset figures large in Middleton's forgotten series of papers on 'Ordering the Strata' published in 1812-1813 (Middleton 1812-1813). These were based on his investigations there in 1812, by which time he had clearly learnt a lot more of the stratification exposed in the south of England, presumably as a result of learning of Smith's work. His papers attempted to list the upper English strata, to which Smith for economic reasons, had been able to pay rather little attention. These ranged from the Brickearth and beds of shells, sand and gravel which overlay the London Clay right down to the Kimmeridge Clay which underlay the Purbeck and Portland strata of Dorset. Middleton claimed his ordering of fifteen separate strata had elucidated a thickness of 3,200 feet of strata, all the way from London down to these strata in Dorset.

Middleton noted in particular the Dorset tobacco-pipe clays, which he wrongly placed below the London Clay. These were then worked at Norden Clay Pits on Purbeck. He noted that these employed 20 men in two pits and that the saleable clay was taken away by a new iron railway to Middle Bere. The Dorset Chalk he estimated to be 800 feet thick. Then, below Wealden rocks which he then calls the Aluminous or Weald Measures (the first time this name was used in British stratigraphy), he described the Purbeck and Portland beds of both Purbeck and Portland, in some detail. Middleton's work in Dorset deserves to be better known. He seems to have worked in isolation (although within the same land-surveying tradition) as had William Smith. Middleton ends his papers with the note that his survey had been "made in a very general way... with the intention of being continued through the whole island when time and opportunity may permit". Sadly this did not happen and no more on geology appeared from his pen, although it did from Smith's. Probably it was the realisation of the progress that Smith had by now made which caused Middleton to write no more.

c) Post 1807 (the Geological Society of London)

Late in 1807 the sadly exclusive Geological Society of London was founded (but to which neither Smith nor Middleton were elected). Others were soon busy in Dorset, in a Britain forced into even more insular attitudes by the long Napoleonic wars. One of the most important was Thomas Webster (1773-1844), who was elected a member of the new Geological Society of London in 1809 and was a fine draughtsman. In 1811 at the suggestion, and with the financial support, of Sir Henry Englefield (1752-1822), he started work on the Hampshire Basin and adjacent areas. He had completed this work by February 1813 but it was not published until 1816 (Englefield 1816). This further laid a foundation for Dorset geology by recording his observations on the rocks from the Kimmeridge Clay to those overlying the Chalk, in the form of letters written from Dorset in 1811 and 1812.

Figure 6. Lecture given by William Buckland (1784-1856).

The formation of the new Geological Society of London soon had, when the Napoleonic wars had ended, a galvanising effect on the progress of Dorset Geology. This was largely due to three people with close Dorset connections. The first was Devon-born Rev. William Buckland (1784-1856), appointed to a readership in mineralogy at Oxford University in 1813 (Rupke 1983). The second was Henry de la Beche (1796-1855), later the founder of the Geological Survey of Great Britain, who had moved to Charmouth and then Lyme Regis in 1812 (McCartney 1977). These two collaborated on a series of fine stratigraphic studies in Dorset, culminating in their joint monograph on the geology of Weymouth (De la Beche & Buckland 1835).

The third member of this triumvirate active in Dorset was Rev. William Daniel Conybeare (1787-1857) who, after Oxford, was

Figure 7. Henry de la Beche (1796-1855).

Figure 8. Rev. William Daniel Conybeare (1787-1857)

appointed vicar of Brislington, near Bristol in 1819. Here he and De la Beche revealed the true anatomy of those two extraordinary fossil reptiles *Ichthyosaurus* and *Plesiosaurus*. The raw material for both of these had come from the even more extraordinary labours of "the greatest fossilist the world ever knew"; Mary Anning junior (1799-1847) of Lyme Regis (Torrens 1995). She had been introduced to the possibilities of making a living by her carpenter father Richard Anning (*c.*1768-1810) but he died of consumption following a cliff fall. She and her young brother Joseph (1796-1849) now took up fossil hunting in an, at first unavailing, attempt to save the Anning family from the Lyme Regis Poorhouse. But her discovery in December 1823 of the world's first complete *Plesiosaurus* made her famous. The realisation soon afterwards, when early accusations of its being a forgery, foisted on the unknowing world of science by Dorset peasants, proved quite unfounded, secured her reputation. She became a vital point of contact at Lyme, both for all the scientists and the tourists who now flocked there to learn more of its treasures and

Figure 9. Mary Anning junior (1799-1847).

to see, and make excursions with, her. In 1828 she found the first British pterodactyl and a whole raft of other magnificent fossils, from invertebrate belemnites to rare fossil fish, were discovered by her in the cliffs around Lyme. She either extracted, or caused these to be extracted, and then developed them and with an extraordinary business acumen, they soon started to fill up the world's museums (see centre spread).

But in 1833 she suffered a financial disaster when her savings were lost by an unknown, unscrupulous and soon dead, investor. By 1845 she was suffering from the breast cancer from which she died an agonising, but we can be sure in her case, brave death in 1847. She was honoured by being elected one of the first honorary members of the new Museum in Dorchester and a long obituary notice, written by the president of the Geological Society of London. This, almost unique for a woman (a group who were too-long barred from membership), was by her old friend Henry de la Beche. She is the first of the two truly remarkable women who have played a part in investigating Dorset's geology.

Mary Anning's work inspired that area of geology, which now brings it its most numerous disciples, namely ‘dino-mania’. Although she never discovered any true dinosaurs here (which were not 'invented' until 1842) in the marine deposits around Lyme (where they have to be very rare) she had inspired the hunt for such fossil remains. The first true dinosaurs-to-be from Dorset were the vertebrae and toe-bones of *Iguanodon*, found before September 1829 in Swanage Bay, weathering out of the Wealden deposits there. These were located by Rev. Thomas Oldfield Bartlett (1788-1841) who was Rector of Swanage from 1817 onwards, and also vicar of Worth Matravers. They were announced to the Geological Society in London on 4 December 1829 and finally brought to scientific attention in 1835 (Buckland 1835, 428). But these specimens were auctioned in April 1841 soon after Bartlett's death (Bonfield 1841) and now seem to be lost.

The World Heritage Coastline ends with the Chalk at Old Harry. The rocks here were first properly investigated in detail by the man

CATALOGUE

OF THE

VERY VALUABLE

COLLECTION OF STUFFED

BIRDS,

RARE FOSSILS,

ANTIQUITIES OF PECULIAR INTEREST &c.

OF THE LATE

Rev. T. O. BARTLETT, Deceased.

SOLD BY AUCTION

BY W. BONFIELD,

Figure 10. Auction catalogue for the collections of Rev. Thomas Oldfield Bartlett (1788-1841)

Figure 11. Book cover of the life of Rev. William Branwhite Clarke (1798-1878).

who later became famous as the 'father of Australian geology' - however misleading such titles are (Etheridge 1878). He was Rev. William Branwhite Clarke (1798-1878). He was Suffolk-born, and a friend of the artist John Constable (1776-1837). After Cambridge University (BA 1821) where he fell under the all-persuasive influence of Rev. Adam Sedgwick (1785-1873) he was elected FGS in 1826. He first published, on geological hammers, in 1828 and then in 1833 was appointed first incumbent of the New Church of St. Mary, Longfleet, near Poole. His salary as perpetual curate here was £45 a year. He had been appointed by William Ponsonby (1878-1855) who had now inherited Canford and the Webb estates. Clarke lived at Stanley Green. He published three major papers in the *Magazine of Natural History* on the Chalk of Ballard Down, on the strata between Durlstone Head and Old Harry rocks and on those of Studland (Clarke 1837-1839). But his salary proved inadequate and in May 1838 he offered his by now considerable geological collections for sale. He lectured to the Blandford Literary and Scientific Institution in September 1838. But in early 1839 he emigrated from Dorset to New South Wales where he was later named 'Father of Australian geology' (Grainger 1982). He died in Sydney in June 1878.

Robert Damon senior (1814-1889) was another important, now Dorset-born, geologist, and a man of great energy, who contributed to the international dimension of Dorset's geology. He was born and baptised at Melcombe Regis in 1814, son of William Damon (1778-1853), an outfitter and hairdresser there. Robert married in 1839 and for a while continued in his father's trade. But he "soon took a great interest in scientific pursuits". By 1847 he was named as the local Weymouth secretary of the newly formed Palaeontographical Society. He was by now selling fossils and by 1849 he was helping Edward Forbes (1815-1854) of the Geological Survey with their new survey of the Dorset coast.

Damon now became active as a natural history dealer based in Weymouth and he was soon selling materials from the whole of the natural world (zoology, conchology, geology, palaeontology, mineralogy etc as well as archaeology) to museums and collectors across the entire globe (for Australian and New Zealand examples, see Sheets-Pyenson 1988, 77-8, 83). The family outfitting business passed to his eldest son William Cozens Damon (1843-1890).

In 1860 Robert published the first edition of his deservedly best-selling book on the *Geology of the Dorset Coast* (Damon 1860, 1884 with several supplements). He was elected F.G.S. in 1864, when he had already been elected a corresponding member of the Imperial Natural History Society of Moscow. He then won a medal at the Paris Exhibition of 1878 and was in 1883 elected an honorary member of the Urals Society for Lovers of Natural History then based in Yekaterinburg (now Sverdlovsk). In 1885 he purchased the famous Godeffroy zoological collections, in Hamburg, which had been made by the great German firm of that name while trading with the islands of the South Seas (Melanesia, Samoa, Polynesia etc). Damon's world-wide activities demanded his world-wide travels, throughout Europe, Africa and even Asia, some of which he described in articles in journals and local newspapers. He died in Weymouth on 4 May 1889 (Anon 1889a) and he deserves to be better remembered, as one of the great museum-builders. His Dorset obituarist rightly noted "he had made for himself a name honoured and respected amongst the leading scientists, of England, the Continent and even Asia on account of his remarkable attainments as a geologist and naturalist" (Anon 1889b). His eldest son Robert Ferris Damon (1845-1925), who had been involved in the natural history agency since 1880, carried this on for some years but finally disposed of most of his remaining stock at auction in 1909-1910. A final auction sale was held in 1929 after his death. A large amount of material had been sold in 1896 by Robert Ferris Damon to the West Australian Museum in Perth. Here it is now being investigated by Professor Ken McNamara. The Damons' important business much deserves further research.

The next Dorset geologist of note is Rev. Osmund Fisher (1817-1914) who was one of the real pioneers of investigations of the physics of rocks and the Earth's crust (Davison 1900, Wilding 1988). Born at Osmington in 1817 he collected fossils here as a

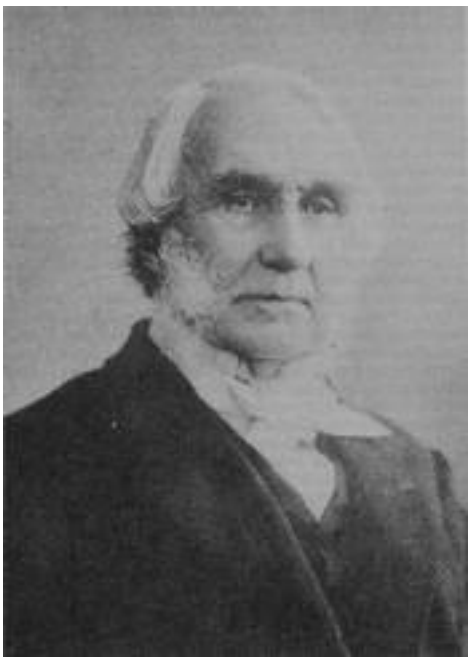

Figure 12. Rev. Osmund Fisher (1817-1914).

small child with his uncle. He settled near Cambridge in 1867. Here he published his magnum opus *The Physics of the Earth's Crust* in 1881. His part in the embryonic investigations of the physics of the Earth are put into context by Wood (1985) and Okeskes (1999).

Edward Cecil Hartsinck Day (1833-1895) is another forgotten Dorset-based geologist. He was born to a Catholic family in Bath and after matriculating at London University in 1850, he married in 1854 and then lived at Box, Abergavenny, Bathford and Weston-super-Mare. In 1859-1860 he attended the new Royal School of Mines in London and now decided on a geological career. To advance this he, in 1861, moved to live in Charmouth, one of the most 'geological' locations in England. In 1863 he was elected FGS and published an important paper on the Middle and Upper Lias of the Dorset Coast (Day 1863). In this he identified a new shell bed in the Middle Lias which is now named Day's Shell Bed after him (Palmer 1966). The ammonite *Dayiceras* was also named after him by L.F. Spath following a suggestion from W.D. Lang (q.v.) "to commemorate [his] important work on the Lias at Charmouth" (Spath 1920, 541).

In 1864 Day purchased "one of the most perfect *Plesiosauri* ever found on the Dorsetshire coast" for £40 from the local dealer Samuel Clark (1817-1898) of Charmouth. As usual Clark's part in this has been forgotten (just as it had been in the case of Mary Anning - Torrens 1995, 280) but was revealed by Casley (1880). The most remarkable feature of this discovery was that in 1864 Day sold it on to the British Museum for £200 (Rolfe *et al*. 1988, 159). Here it survives as NHM 38525 (holotype of *Plesiosaurus rostratus* Owen). Day was highly active as a geologist while he was at Charmouth. He helped Huxley with his researches on belemnites. In 1865 he revealed the true situation of the cephalic spines in the fossil shark *Hybodus anningae* (Day 1865) and in 1867 he acquired from Isaac Hunter (1833-?), another Charmouth collector, a second new species of *Plesiosaurus*, which Richard Owen was to have called *Plesiosaurus laticeps* (Davies 1867). This too passed to the British Museum (NHM 40140) but it was never described by Owen.

Samuel Clark, one of the most important post-Anning Lyme area collectors, was also the discoverer, in 1879 of the holotype specimen of *Plesiosaurus conybeari* Sollas (the same species as *P. laticeps* was to have been!) This was purchased by Bristol City Museum in 1881 (Cb 2479) where it was destroyed in WW2, and where only photographs now survive. But a cast survives in NHM (R1338) and this was later used as the type species of a new genus named *Attenborosaurus*. Its dedicatee, the broadcaster David Attenborough, has since invented an extraordinary story involving its discovery by Mary Anning (Attenborough 2002, 324) but she had been dead over 30 years when it was found!

While based at Charmouth, Day was employed in 1864-5 by the engineer Sir John Hawkshaw (1811-1891), before the formation in 1872 of his English Channel Company. This was to undertake a pioneering, but private, geological survey of the route for a planned Channel Tunnel. It was undoubtedly his association with the Royal School of Mines and the Geological Survey which secured Day this job. In 1914 Hawkshaw's son John Clarke Hawkshaw (1841-1921) described the history of this (Hawkshaw 1914) and Day's forgotten part in this:

"Early in 1865 Sir John obtained the services of Mr Hartsinck Day, who, besides being a competent geologist, had also a knowledge of surveying. Mr Day's attention was directed principally to the cretaceous beds which Sir John's large experience in tunnel work led him to choose as the most promising material through which to tunnel. Mr Day spent several months... surveying the beds on the coast in England and France, and prepared a geological map showing their position on both sides of the Channel as to the position of the beds under the sea" [which is reproduced between pp. 600-601].

The route that was chosen was very similar to that now in operation, and was also carefully chosen to pass mostly through the Lower Chalk. This tunnel was to have crossed from Calais, close to the present terminal at Sangatte, to end in St Margaret's Bay, to the east of the present exit at Shakespeare Cliff, until it was brought to a complete halt by the British Government (and the British Military) in 1883. By this time Day had long been working in the USA where he had taken up a post as "assistant in assaying" in the School of Mines, Columbia College, New York in 1866. He then became in 1872, Professor of Natural Sciences at the Normal College, New York, where he was also active as a botanist. He died on 4 January 1895 in Algiers, whilst on tour in an attempt to recover his health (*Times*, 12 January 1895, 1).

Just before Day had started his Channel Tunnel survey the Royal Agricultural College at Cirencester had finally dispensed with the remarkable services of its long serving, and badly served, Professor of Geology, Botany and Zoology; James Buckman (1814-1884) (Buckman 1863). He lost his job here largely for reading a paper to the BAAS on the botanical experiments he had made at Cirencester. These supported Darwin's evolutionary theory, which had dangerously appeared just before in 1859. Buckman had had the misfortune to read his paper the day previous to 'the great debate' between Huxley and Wilberforce at the famous Oxford BAAS meeting on 30 June 1860. This was widely publicised to Buckman's detriment (Torrens 1988).

So in July 1863 Buckman moved with his young family to settle at Bradford Abbas in North Dorset, starting thereby a twenty year long association with this county. This soon led to the formation

of the Dorset Natural History and Archaeological Society in 1875, which still flourishes. He edited their early *Proceedings* and published widely on the geology of Dorset but a more permanent, if much debated, influence on that subject came from the work of his eldest son, Sydney Savory Buckman (1860-1929) (Torrens

Figure 13. Sydney Savory Buckman (1860-1929) in 1907 painted by his brother Percy (1865-1948).

2004). He attended Sherborne School between 1871 and 1879, along with Alfred North Whitehead (1861-1947) O.M. who later memorably wrote about the inspiration such an historic town could have on all who study geology, archaeology or human history (Whitehead 1948, 26-33).

Sydney Buckman was certainly one inspired by these remarkable surroundings with “intimate scenery such as, in all the world only the West of England can provide [amid a] kindly peasantry who had an English dialect of their own which [Whitehead] could hardly understand. They were a kindly folk; if a schoolboy on a country walk asked for water, he was given cider and no payment taken” (Whitehead 1948, 27, 32).

Buckman junior made three vital contributions to geology (and one that was then taken as very negative!) The positive ones were

a) that rocks could be very precisely dated using ammonites

b) that rocks of the same lithology when so dated could prove to be of very different ages. He first demonstrated this on the Toarcian to Aalenian sands which stretch from the Dorset coast (there called Bridport Sands) inland as far as the Cotswolds (now called Cotswold Sands). These same rocks are those that provided a hiding place for the main protagonist in the best novel yet written to directly involve Dorset's rocks: Geoffrey Household's just pre-World War Two *Rogue Male* of 1939 (*The French Lieutenant's* involvement with rocks was sadly less direct). Buckman's 1889 analysis of this rather new geological phenomenon - diachronism - has survived over a hundred years of later analysis (see Callomon & Cope 1995, 60).

c) that when rocks were so precisely dated, the records they revealed of their depositional histories proved often to be incomplete. This was due both to periods of original non-deposition (as with historical archives - on which this paper should have been based - where records have simply not been kept) or later periods of erosion (where, in history, records later get thrown away). Buckman's classic study of this phenomenon was worked out on the complex deposits of the Middle Jurassic Inferior Oolite in North Dorset. His work here has been the subject of a masterly survey by Callomon (1995).

The one negative aspect of his work was that he saw the need to recognise many more generic and specific names for his ammonites than were then thought necessary.

Aspects of practical geology in Dorset

While all this academic study was progressing, those needing to use at least some basic geological knowledge in their practical operations in Dorset were still busy. But, when these failed, whether hunting for “true coal” in the Lias at Lyme Regis or for the same material at higher levels near Weymouth, records of these activities have been significantly non-deposited (in the Buckmaniac sense) since history simply does not record the history of losers or that of failure, in the same way that it records that of winners and success. But enough can be gathered to show that much practical activity in Dorset in the last 30 years of the nineteenth century was singularly devoid of any geological basis.

Buckland Ripers

In August 1872 there was much excitement in Dorset, and farther afield, when a reputed seam of coal was discovered in Paynes Copse, at Buckland Ripers, near Weymouth (*Dorset County Chronicle*, 29 August 1872, 3). The site was owned by the Churchill family, of Colliton, Dorchester; either George Churchill (1811-1889) or his son George Onslow Churchill (1838-1921 - who had been born at Buckland Ripers). By 31 August 1872 a five feet square shaft had been dug down nearly 20 feet, by four men (*Times,* 31 August 1872, 6). It was reported that they would only need to reach the depth of 80 feet to find "good coal" and that the discovery would be "of immense importance" to Dorset and of considerable profit to its owner.

By 4 September the work was being much retarded by water and now steam power was needed to pump all the water out, with the shaft still not yet 40 feet deep. It was further reported that this discovery had "created considerable interest in Dorset, especially as iron ore has, it is stated, been discovered in the neighbourhood of Abbotsbury not far from Buckland Ripers" (*Times*, 4 September 1872, 5). Next day it was revealed under a heading "The Dorset Coalfield" that "several years ago Buckland Ripers was regarded as likely to become a promising coal district and excavations have from time to time been made in search of the 'Black Diamonds'".

This shows that once again the usual 'old wives tales' of the presence of coal here had long existed, but that any knowledge of the basics of geological science had certainly not yet reached this part of Dorset (*Dorset County Chronicle*, 5 September 1872, 4). By 16 September the shaft was still only 35 feet deep, since water had completely stopped work, "although the demand for coal, at Cardiff was brisk" and its price now high! (*Times*, 16 September 1872, 6).

Local doubts of the viability of this 'enterprise' were only first raised on 19 September. But these only related to the technical difficulties that had been encountered, with water. "It would be a

pity the enterprise should be given up now it has proceeded so far, and when it really does appear a coal-field exists at some depth below that already arrived at" (*Dorset County Chronicle*, 5 September 1872, 4). An anonymous correspondent had earlier warned in a letter (BGS archives 1/1181, James Buckman press cuttings, volume 3) after a personal visit that the claim that coal had already been found needed to be "taken with a grain of salt". His visit had convinced him that the "unqualified assertions which were current in Dorchester at the beginning needed modifying" since "no seam of coal had been found". It was only the enormous increase in the price of coal nationally which had fostered this enterprise, he said, but he ended by noting "Coal at Buckland, and iron ore at Abbotsbury, would soon make Dorset a manufacturing county. Let us hope it may be so, and that we may all share in the prosperity it would bring" (*Weymouth, Portland and Dorchester Telegram*, 30 August 1872, 9).

Scientific doubts over this lunacy do not seem to have been raised. James Buckman at least, based in North Dorset, who had had considerable experience as a coal prospector, both in England and in North America (Torrens 2002, XIII), does no seem to have been consulted. But **his** local paper did soon correctly note that this search was "absurd" and that "no doubt shale will be found but no coal" (*Sherborne Journal*, 19 September 1872, 8). Perhaps this was at his instigation?

Nevertheless it was soon reported elsewhere (*Dorset County Chronicle*, 19 September 1872, 3) that "an attempt is being made to form a company for the purpose of continuing the operations" and that the services of "a practical miner from the North had been engaged, who was confident, if they went down about 40 feet deeper, the coal stratum would be reached"! This must have been, the mining engineer George Sheppard (c.1823 - ?) of London, although he was born at Wellington, Shropshire. On 23 October he gave his written advice, to George Symonds confirming that he thought the black clay found here did "very closely resemble" that in our Coal Series and urged that they continue to prove the strata here down to 450 feet! Symonds was a farmer at nearby Winterbourne Monkton, who sent a copy of the letter (GSL, Moore archives) on to the geologist and fossil collector Charles Moore (1815-1881) of Bath who had leased the above mentioned deposits of Abbotsbury iron ore in May 1872 (Groves 1887, 66).

Some expected connection between the hoped-for coal at Paynes Copse and the occurrence of this Lower Kimmeridgian Iron Ore at Abbotsbury is thus clear. This ore had been 'discovered' by at least 1849, when the Geological Survey of Great Britain reported on it and found it to be between 30 and 49 feet thick with up to 46% iron (Damon 1884, 48). In the 1850's there was a new interest in such brown haematitic iron ores from the Jurassic, inspired by revelations made at the Great Exhibition of 1851 (Hunt 1864, 225-6). These demonstrated the possibilities of such iron ores in Northamptonshire and duly inspired a rash of attempts to find coal there as well. Another ore was the Cleveland ironstone in Yorkshire, described by Joseph Bewick (1816-1862) in his *Geological Treatise* of 1861. Then in 1863 Charles Moore of Bath gave a paper at the BAAS meeting in Newcastle-on-Tyne (where such supplies of iron ore were most needed), on "The equivalents of the Cleveland Ironstone in the West of England". This focussed attention on the Dorset ore and on 22 May 1872 Moore himself leased the Abbotsbury deposits (Thomas 1995, 63). Moore was an informed and knowledgeable geologist who has usually been

Figure 14. Charles Moore (1815-1881).

assumed to have been able to remain an enthusiastic 'amateur' thanks only to the wealth of the woman, Eliza Dear, whom he had married in 1854 (Torrens & Taylor 2004). But it now becomes clear that he was also a considerable speculator in British mineral deposits.

But suddenly, between 5 August and 25 October 1872, Moore sold his iron ore lease to the South Wales mining engineer and industrialist Sir George Elliot (1815-1893) M.P for Durham North. He had been a member of the recent Royal Commission on Coal in the United Kingdom, which had reported to both Houses of Parliament in 1871. Elliot was created a baronet in 1874 (Anon 1874). Elliot had been the head of a major firm of wire rope and electric telegraph makers from 1849. His firm had proposed to build an Abbotsbury Wire Rope Tramway, as early as late 1870, to take the iron ore away to be smelted in South Wales where Elliot had large mining and metal working interests. But as soon as it became clear that crazy attempts to use "local coal" instead were to be involved, Moore seems to have decided to give up his lease at Abbotsbury. The site of Paynes Copse needs to be located before we can be sure in exactly which stratigraphic horizon these misguided coal hunters were hoping to find their 'black diamonds'. The area around here is badly faulted with Forest Marble and/or Oxford Clay faulted together. Either are likely to have misled these coal hunters, as both display exactly the same similarity in mere lithology to that of true Coal Measures of which William Smith had warned nearly seventy years before (Torrens 2003b).

Lyme Regis

Nor was this 'the last such clutched straw' in Dorset. That people should be hunting for such an expensive - to procure - mineral as coal, well over 60 years after William Smith's *Geological Map*, published in 1815, had shown how impossible it was to find this material here (Torrens 2001), was bad enough. But Buckland Ripers was by no means the last attempt to 'industrialise' Dorset. An even more ill-advised attempt was made near Lyme Regis in 1901. Again this was a total failure and again the history of the failure has been 'non-deposited' as far as its record on paper goes. The 'rock record' of it is much better, thanks only to Alfred Capper

Pass (1837-1905) of nearby Wootton Fitzpaine, after whom the chair of chemistry at Bristol University was named and endowed. He stepped in to extend this stupid operation before it was abandoned so that all possible geological information at least could be gathered from it down to a depth of 1300 feet (Taylor 1989). Work here had certainly started by 17 January 1901 when the local paper reported that "boring operations were in progress on Middle Hill Fields, near Horn Farm, in the hope of finding coal" (*Dorset County Chronicle,* 17 January 1901, 6).

The superintendent on the spot was George Haycraft (1832-?) born at Honiton. He is recorded as a cement maker at Lyme Regis in the 1881 Census. By 1895 Haycraft and Co. were lime and stone merchants at the Cobb, Lyme Regis (Draper 2001). There seems then to have been considerable competition in Lyme cement-making. In the 1901 Census, George is recorded as a civil engineer at Lyme, since he had now sold on his interests in Lyme cement-making on. He had sold these to a new company, the Lyme Regis Cement Company of 1899 which intended to erect new works at Lyme (*Times*, 6 March 1899, 14). A view of the Lyme Cement works in the late 1890s appears in Fowles (1990, photograph 91).

The five Directors of the new Company include:

1) the chairman Hon. John Augustus De Grey (later 7th Baron Walsingham) (1849-1929), London barrister,
2) his brother-in-law John Cameron Grant (1857-fl.1916), London civil engineer and poet
3) Henry John Davis (1842-?), London, Gas Stove Manufacturer and chairman of the Davis Gas Stove Co. Ltd, London
4) his probable relative, J.H.G. Davis, Halifax, chairman of the Madeira Electric Lighting Co. Ltd.

Later Francis Caffin (1857-?), Marlow, retired engineer and railway contractor was to join them (Francis 1977, 178).

There seems to be no evidence that any had geological knowledge. The problem here again seems to be that the coal hunters expected coal at a shallow depth (less than 600 feet according to Jukes-Browne 1902, 279), just as at Buckland Ripers. On the other hand geologists, as represented by the president of the Geological Society, thought that "no geologist, probably, would have recommended this borehole from an economic point of view" (Jukes-Browne 1902, 288). There seems no record of the detailed rationale behind the attempt here. But in view of the location, it seems highly likely that the locals had once more been confused by the simple lithological similarity of the black Lower Lias clays at Lyme with those found stratigraphically much lower, in economically viable, Coal Measures. But, if these hunters had known even the rudiments of geology, they should have known better. Even if they instead expected coal immediately below the Trias cover here, then they were to be defeated for exactly the same reason that had defeated William Smith nearly a century before, at Compton Dundon in Somerset, not that far to the North in 1813-1815 (Torrens 2001, 70). This was because of the extraordinary thickness of Triassic cover in this area.

The Twentieth Century

Dorset continued to have a number of significant geologists living here, such as Wilfrid Hudleston (1828-1909) who wrote the *Monograph on Inferior Oolite Gastropods* published 1887-1896 and who was a vice President of the Dorset Field Club. He had a country estate at West Holme, near Wareham and here he died in 1909. His library clearly stayed in Dorset, where I bought a considerable amount of it in the 1970s. But Hudleston remained essentially a nineteenth century figure.

A more significant Dorset geological figure is one more certainly of the 20th century, since he had been inspired by the work

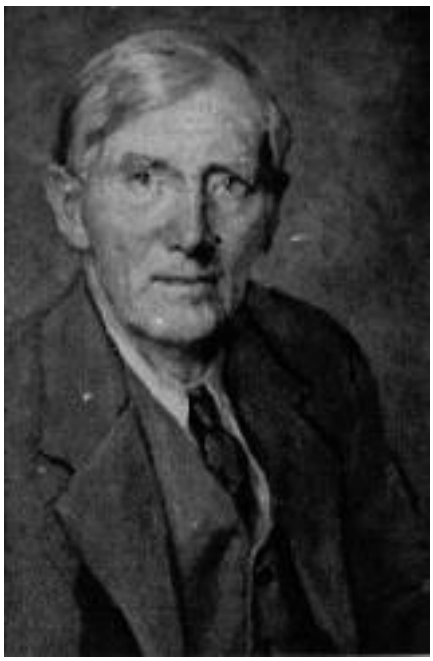

Figure 15. William Dickson Lang (1878-1966).

(described above) of S.S. Buckman (White 1966, 376). This was Indian-born William Dickson Lang (1878-1966) who in 1898 was already visiting Charmouth during Cambridge undergraduate holidays. He then became Keeper of Palaeontology at the British Museum (Natural History) where he worked 1902-1938 before retiring back to Charmouth. Lang made major contributions to our detailed stratigraphic knowledge of the Liassic rocks here which he also mapped in great detail (1/2500) and he also published a number of significant studies of Mary Anning.

The Geological Survey of the United Kingdom were busy in the 1930's re-mapping Dorset and one of those most involved was a Survey officer who has been completely forgotten. He is Dr. Francis Brian Auburn Welch (1903-1987) who after Cheltenham College and Bristol University (first class honours in geology 1924, Ph.D. 1927) went first as a research assistant to St Andrews University. He joined the BGS in 1931 and was sent to Dorset where his maps made between 1931 and 1936, whether as manuscript field slips at 1/2500 or the published one inch to a mile sheets, like that of Bridport Sheet 327, published in 1940, are miracles of geological map-making. As W.J. Arkell rightly wrote to P.C. Sylvester-Bradley on 9 October 1948 (when this last map was finally reprinted) "I have at last secured a copy of the Bridport Sheet. What a lovely bit of work" (Arkell archives, OUM - see Alton 2002). Welch died on 1 March 1987 in Cheltenham (*Times* 3 March 1987, 15)

The Dorset geologist of the 20th century was undoubtedly William Joscelyn Arkell (1904-1958). Born at Highworth, Wiltshire to the well-known brewing family there, he went first to Durlston Court Preparatory School near Swanage, which revealed the delights of Dorset to him and then to Wellington College.

Figure 16. William Joscelyn Arkell (1904-1958)

After a first in Geology at Oxford in 1925, he was awarded the Burdett-Coutts scholarship there. This opened the way for his geological researches to continue. He soon became master of the Jurassic, at first in Britain (Arkell 1933 - a remarkable achievement for one still in his twenties) and later the world (Arkell 1956). Private means had helped, as had his bungalow at Faraway in Ringstead Bay, where visiting geologists were often entertained. His major work on Dorset was the *Weymouth, Swanage and Lulworth Memoir* (Arkell 1947). This had reached galley proof stage by 1939 but its publication was thwarted by the war. In this Arkell (1947, 9) wrote most movingly of the urgent need to guarantee a future for the Dorset Coast and so we should think of him as **the father** of the Heritage Coast project.

The same issue of the *Proceedings of the Geological Society of London* (no. 1572, 1959) which contained an obituary notice for Arkell also gave notice of the passing of another Dorset geologist who deserves to be remembered. This is Dr. Marie Stopes (1880-1958). She is rightly only now famous as a pioneer of birth control, work which saw her voted "the second most influential woman of the 20th century" after Emmeline Pankhurst (*Observer*, 29 June 1997). But her early work as a palaeobotanist was of real significance. Her connections with Dorset started in 1923 when she bought the Old Higher Lighthouse (now a guest house!) on Portland Bill. Here her only surviving child was fittingly conceived in 1923, a fact of which she wrote "in phrases purpler than any Homeric sea" (Hall 1977, 247-8). But she kept up her interests in geology and her last paper was the description of a fissure she reported in a Portland quarry. It contained human skulls, animal bones and stone artefacts (Stopes et al. 1953). Her co-author was Kenneth P. Oakley (1911-1981), one of those who was to expose the Piltdown jaw as a fraud in the same year (Weiner et al. 1953). Marie Stopes should also be remembered for her purchase of the premises in which she founded the Portland Museum.

Since some part of what was Hampshire is now placed in Dorset (and enables me to claim Dorset birth), I should mention the leading geologist of the Hampshire basin at this time, Ernest St John Burton (1875-1962). He was born at Parkstone, son of the

Figure 17. Dr. Marie Stopes (1880-1958).

Bournemouth organist and prolific composer Thomas Arthur Burton (*c.*1842-fl.1919). Ernest trained as a musician at the Brussels Conservatoire Royal de Musique, at the insistence of his father, and played for some years, around 1903, among the first violins of the Bournemouth Municipal Orchestra. But his first interest was always in art (Anon. 1925, 15-17). His first surviving paintings known to me are a fine series of the Dorset Coast near Lulworth and Durdle Door dating from 1906. In a remarkable career change caused by the First World War, Burton next became a prolific and highly professional painter of landscapes who exhibited here and in Paris between 1926 and 1958, whether in pastels, oils, tempera or water-colours. His hobby was natural history and he was progressively elected F.G.S. (1923), F.Z.S. (1924) and F.L.S. (1927). Geology however remained his forte and he published a number of important papers on the geology of both Dorset and Hampshire from 1925 up to the Second World War. Who today would dare to even try to excel as a musician, a painter and a geologist?

After the last of these people had died, we move into more difficult historical times (since I remember them better). Jo Thomas and Paul Ensom's fine bibliography (Thomas & Ensom 1989 and

<www.dor-mus.demon.co.uk/gbibcontents.html>)

gives full details of what has been published and where to locate full bibliographic references. I would however like to pay a personal tribute to some few:

1) Rev. Joseph Fowler (1872-1958), without whom I would not have become a geologist, was a retired clergyman and schoolmaster who settled at Sherborne in 1934 and thereafter kept a careful eye on all temporary exposures (and all aspiring geologists, of which I was one) in that area (Fowler 1959).

2) Professor Peter Sylvester-Bradley (1913-1978) was the most charismatic teacher I have ever come across (and how I should know!) His parents owned Langton Herring Manor House and here in the nearby churchyard they lie buried. This place inspired

Peter with a love of Dorset, on which he wrote a number of important papers before his untimely death (Whitaker 1980).

3) Professor Michael House (1930-2002) born at Blandford and who, at Arkell's suggestion took up the study of Devonian rocks, on which he became a world authority (to rival Arkell's on the Jurassic). He retired to Weymouth where he inspired local geologists and continued to publish on Dorset geology, culminating in his *Geology of the Dorset Coast* (House 1989), (Neale 2002).

4) Professor John Callomon (born 1928) who, trained as a chemist but inspired by Arkell as an undergraduate, continues to make major contributions to both stratigraphy and palaeontology. Working to great effect on Dorset's (and most other places!) Jurassic rocks he has shown us with what precision the geological record can be studied (Callomon 1995). He was responsible for the most important advance in our knowledge of ammonite palaeontology of the last half century; the importance of recognising the considerable sexual dimorphism shown by ammonites (see Surlyk 1994).

This survey has understandably given a rather personal view, but I hope it has confirmed what an extraordinarily long history Dorset's geology has had. This puts it on a par with the quality of those same, now famous, rocks.

Abbreviations

BGS = British Geological Survey

DCM = Dorset County Museum

GSL = Geological Society of London

NHM = Natural History Museum, London

OUM = Oxford University Museum of Natural History

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To the late Victor Adams, John Callomon, Claudine Cohen, John Fowles, late Michael House, late Harry Johnson (Poole), and the many archivists and librarians who have so helped me.

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Book review

The Earth – an intimate history, Richard Fortey, 2004, Harper Collins, 501 pp., £25 (hardback), ISBN 0002570114.

Richard Fortey has done it again. After explaining to the general reader the geological formation of the British Isles in The Hidden Landscape and the history of life in Life – an unauthorised biography (not to mention his delightful book on trilobites), he has tackled the whole Earth and all of geology in this long, discursive, immensely attractive volume. His style leads one on through personal reminiscences of places which have been important in the growing understanding of geology (Naples, Hawaii, the Alps, Newfoundland, the Deccan Traps, the San Andreas Fault…) and through all the good tales of the history of geology (the Granite Controversy, the Highlands Controversy, the saga of Continental Drift…) Constantly he lets fall words of wisdom: "…geology always turns out to be more complicated than was thought at first…"; "geology informs almost everything on our planet, and is rich with human entanglements…The progress of our understanding is also inextricably linked with the virtues and failings of the investigators…"; "As St Luke's gospel puts it; 'the truth will set you free', and once the continents themselves had been untethered so, too, scientific imaginations were liberated to pursue their dreams." It is the "untethering" of the continents which lies at the heart of the book: he says in the preface that he has " been thinking how best to describe the way in which plate tectonics has changed our perception of the Earth." and the chapter entitled "Plates", chapter 5 of the 13, feels like the heart of the book.

Chapter 10, "The Ancient of Days", is a good example of his method. By now he is turning the reader's attention to the very distant past. He begins with a description of the Scottish geologist J. J. H. Teall in the little fishing village of Scourie in the far north-west of Scotland in 1883. (Heroic pioneers in the history of geology are given generous space throughout the book.) Having established the significance of the discovery of Lewisian gneiss, and dykes at completely different orientation from the Caledonian, Fortey then goes there himself with a modern expert (Graham Park). There is much description, most attractively done, of the landscape and the crofting system; and effortlessly we have been brought to wonder at granulite facies. "We are looking so far back in time that ghosts and chemistry are our best informants" (he has just talked of "mere ghosts of crystals of feldspar"). We then move to consider the Moine Thrust and the Torridonian, and affectionate mention of the Olenellus trilobites reminds one quietly that again and again there are hints of his own credentials as a respected palaeontologist. Gradually we are brought to consider the whole Precambrian, radiometric dating, structural geologists "read[ing] the flexures in the rocks with the certainty of a blind man reading Braille", BIFs, the accretion of cratons. We are helped along by strangely apposite quotations from Walter Scott and John Keats – the latter's

> "Time, that agèd nurse,
>
> Rocked me to patience"

was used near the beginning of the book, and gives a sense of linkage in the story. When we come to the "strangeness" of the earlier Precambrian, and especially its completely different atmosphere, the famous opening of The Go-between is used with a new twist: "The past is another country. They do things differently there." We look at early super-continents, rapakiti granite (as the counter of a bar at Paddington!), the 'Snowball Earth' hypothesis (briefly but judiciously considered – especially the implications for life of Kirschvink's "upping the stakes" by postulating more than one episode: wickedly paraphrasing Wilde, Fortey quips that "to survive one snowball is fortunate, but to survive several looks like miraculousness"!) We are taken back to the earliest rocks on earth, to the Hadean, to the oldest zircon crystal yet found. And then in a brief epilogue we are back where "the eternal sea breaks heavily over the Lewisian gneiss and the dykes of Scourie", and end with the growth of geologists' understanding, and with Fortey's meditations on the scene, as poetic as anything he quoted, and so effective at making us feel, if not comprehend, the immense process that is the history of the Earth.

Professor Fortey writes with all the authority of not only a leading palaeontologist, but one who has made significant contributions to palaeogeography (the co-discoverer of Tornquist's Sea), deservedly an FRS as much for his popularising of Earth sciences as for his professional attainments, and on the evidence of all his books, a widely read and deeply humane man at home in both the Two Cultures. A book to give your non-geologist friends and relations, to enthuse them as much as you have been by your studies; also a book for yourself, to remind you of so many points that you learnt as you progressed through OU Earth science courses and now are just a bit hazy about; a book to suggest yet more fascinating places to go to on OUGS trips!

I've quoted a lot but can't do better than end with more of his own words:

"Geology acts as a kind of collective unconscious for the world, a deep control beneath the oceans and continents…For the general reader, the most compelling part of geological enlightenment is discovering how geology interacts with natural history, or the story of our own culture…

"The problem is how we marry these two contrasting modes of perception – the intelligent naturalist's sensitive view of the details of the land with the geologist's abstract models of its genesis and transformation..."

Philip Clark, BSc Hons (Open), MA (Oxon).

The Jurassic Coast: a geological overview

Chris Wilson, Professor of Earth Sciences, The Open University

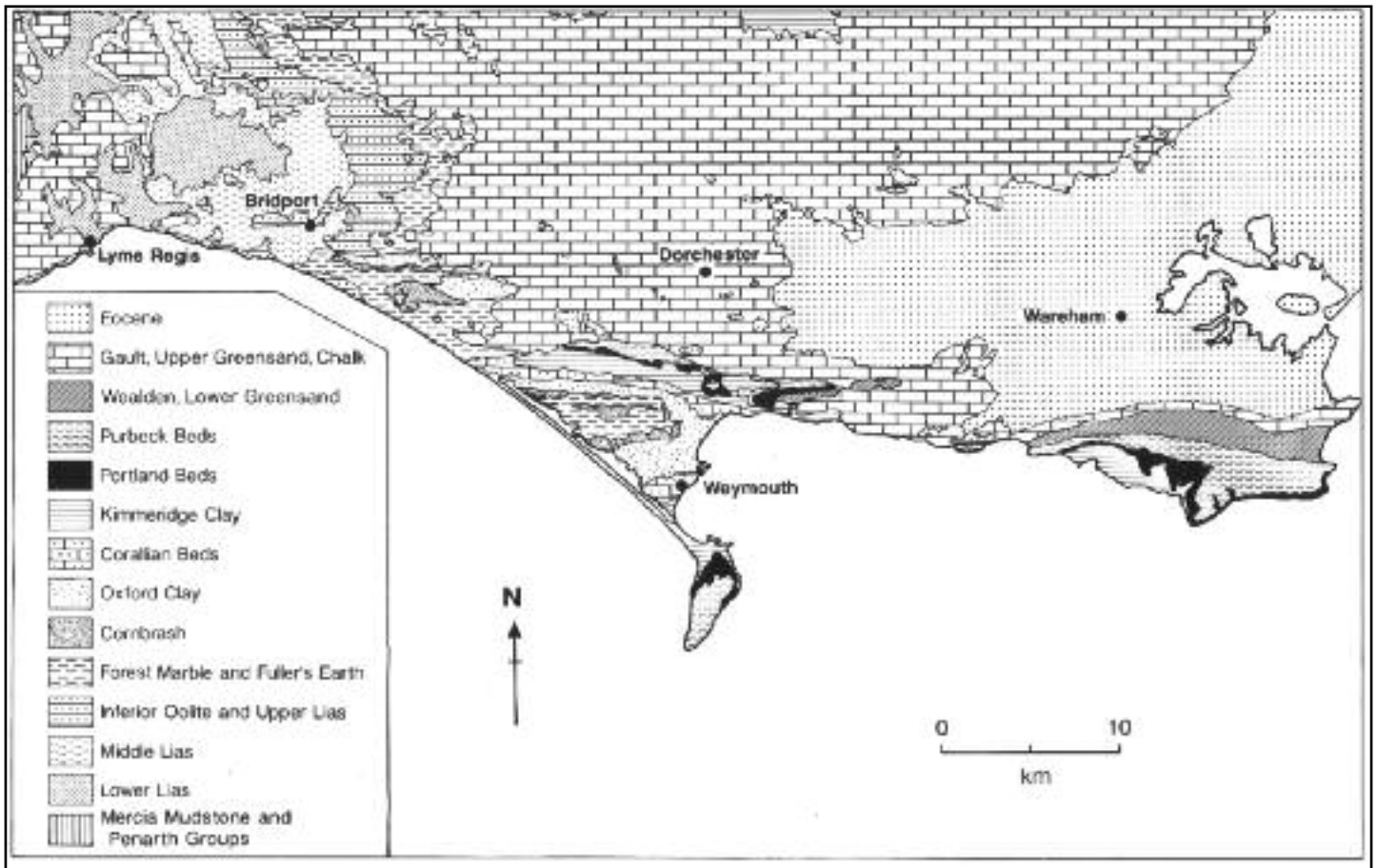

Figure 1. Geological map of the Dorset part of the 'Jurassic Coast'. From Callomon & Cope (1995).

"In December 2001 the 'Jurassic Coast' was awarded World heritage status and became recognised as a place of outstanding universal value. Its 155 kilometres of dramatic cliffs, tumbling landslides, spectacular arches and sea stacks display 185 million years of the Earth's history…… It is a place of understanding and enjoyment, a scientific asset and an educational resource" From the Foreword by Prince Charles to the Official Guide to the Jurassic Coast (Brunsden, 2003)

Introduction

The purpose of this paper is to provide an overview of the geology of England's first natural World Heritage Site in order to place in context the other papers presented at the Society's annual symposium held in Dorset in July 2004. It will answer three questions:

- Why is an almost complete record of the 185 million year long Mesozoic Era exposed along the coast of East Devon and Dorset?
- Why do the exposed rocks get progressively younger from west to east?
- Why are there contrasting structural features displayed in the Lyme Bay and Weymouth Bay – Isle of Purbeck areas (namely many normal faults in the west, and a few large faults and major folding in the east)?

The evidence needed to answer these questions is presented in four parts:

1) the intra-Cretaceous unconformity
2) a very broad stratigraphic overview
3) a structural overview
4) the role of salt in structural evolution.

The intra-Cretaceous unconformity

Figure 1 is a geological map of South Dorset. To the west of Lyme Regis it shows Upper Cretaceous rocks resting unconformably on the Lower Jurassic. Further west, into East Devon, the Upper Cretaceous oversteps onto Triassic rocks, a relationship that is well displayed in the cliffs between Seaton and Budleigh Salterton. At the other side of the map, some 15 km south-east of Wareham, an almost complete succession from the Upper Jurassic to Upper Cretaceous is exposed along the coast. In a broad area to the north of Weymouth the Upper Cretaceous is juxtaposed against a number of Jurassic units by faulting, but the faults are not identified on the map. The main fault, the Abbotsbury-Ridgeway Fault, is shown on Figure 2, which is a simplified representation of the intra-Cretaceous unconformity and the overall easterly dip of the Mesozoic succession. On the west side of the diagram the Upper Cretaceous (Upper Greensand and Chalk) is shown resting unconformably on Permian sediments. In fact just to the south of the Haldon Hills it rests on Upper Palaeozoic rocks. In contrast, on the east side of the diagram there is an almost complete succession of Mesozoic strata,

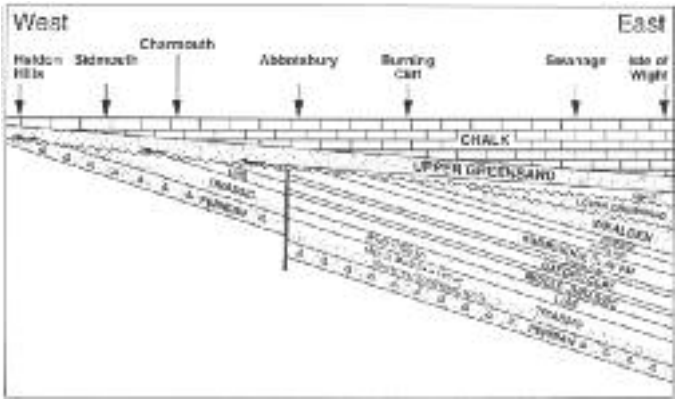

Figure 2. Diagram showing the general eastward tilt (true dips not shown) of Mesozoic strata along the 'Jurassic Coast' and the intra-Cretaceous unconformity. The length of the section is about 100 km. From Underhill & Stoneley (1998).

interrupted only by small unconformities between the Gault and Lower Greensand, and Lower Greensand and Wealden.

Stratigraphic overview

Figure 3 shows, on the left, a very simplified stratigraphic summary of the 'Jurassic Coast' and Isle of Wight, and on the right the key tectonic episodes that affected the area. Some of the stratigraphic features shown on this figure are amplified and/or explained below:

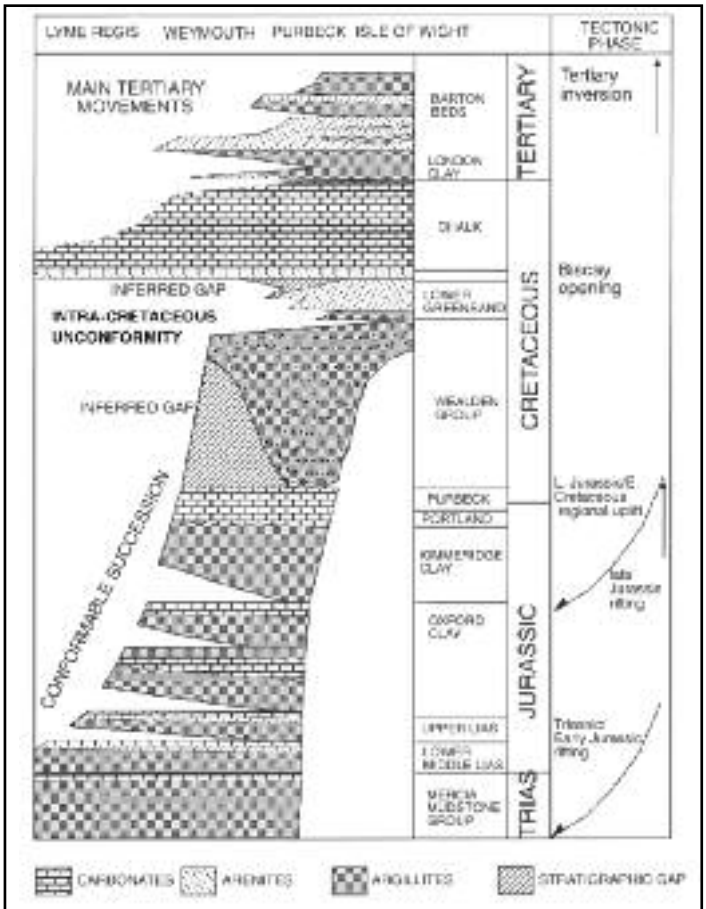

Figure 3. Simplified stratigraphic chart showing the lithostratigraphy of the Jurassic coast and Isle of Wight areas, the intra-Cretaceous unconformity, and associated tectonic events. Further explanation in the text. Modified from House (1989) by McMahon & Turner (1998).

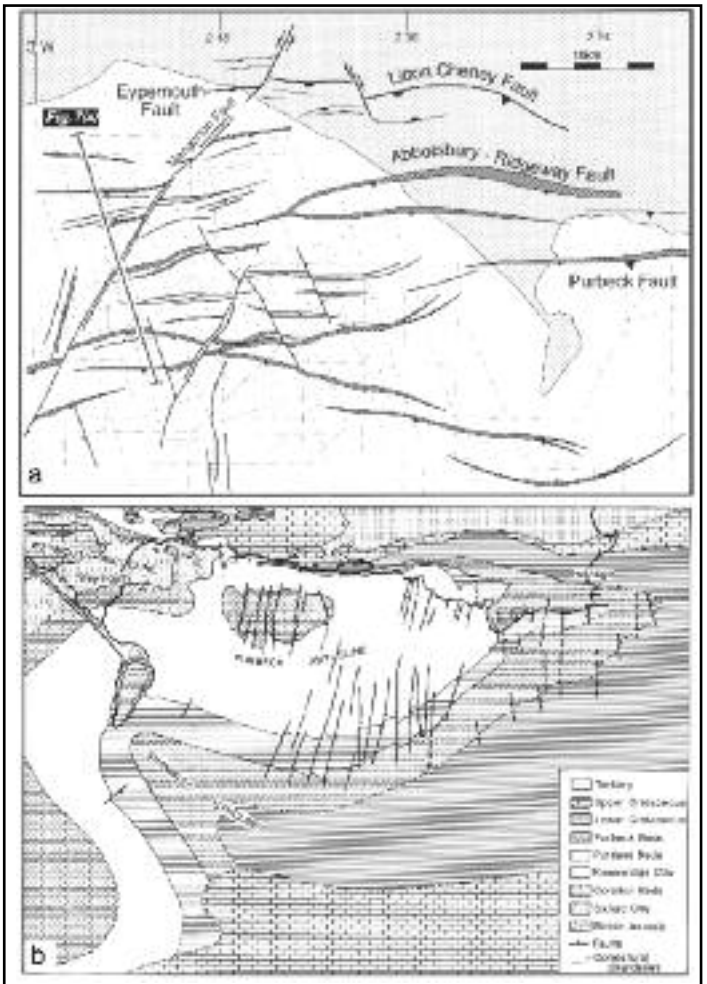

Figure 4. Contrasting structural styles in the areas adjacent to the western and eastern parts of the Jurassic Coast. For further explanation, see text. (a) Map showing faults in the Lyme Bay area, mapped at the base of the Jurassic (from Harvey & Stewart, 1998). (b) Map of the onshore and offshore geology between Weymouth and Swanage (from Callomon & Cope (1995) after Donovan & Stride 1961)). To the NE of Weymouth, at the northern edge of the map two periclines are visible: these are situated at the eastern end of the Abbotsbury Fault.

- continental deposits, mainly fluvial in origin, occur in the Triassic and Wealden. The red argillites in the Triassic Mercia Mudstone Group also contain some sandstones, and near the base, interbedded halite and mudstone up to 500 m thick. The evaporite unit is not present at outcrop, but halite pseudomorphs are known from the equivalent interval.

- a major marine transgression occurs across the Triassic-Jurassic boundary, with the Jurassic marine argillites being dark grey rather than the red colour of those of the Triassic below. This transgression is a reflection of the global sea-level rise caused by an increase in rates of sea-floor spreading that accompanied the break up of the supercontinent of Pangaea.

- The inferred gaps beneath the intra-Cretaceous unconformity refer to the implication that the Wealden and Lower Greensand were not deposited, rather than being deposited and then eroded before the Late Cretaceous transgression that resulted in the deposition of the Upper Greensand and Chalk.

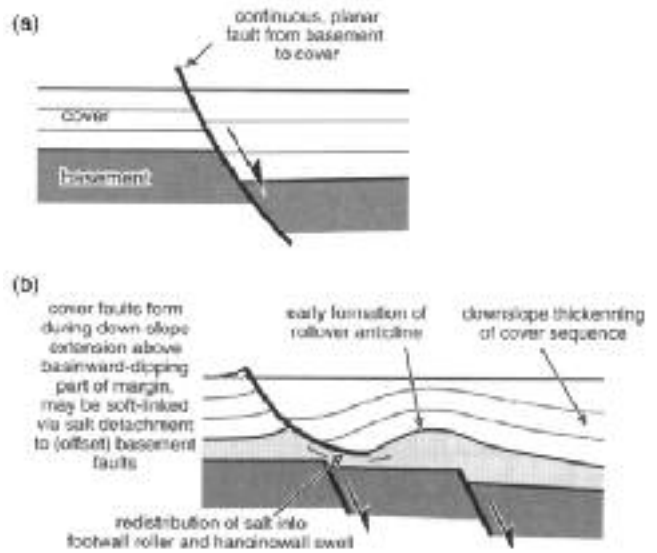
(a)
continuous, planar fault from basement to cover
Cover
Basement
(b)
cover faults form during down slope extension above basinward-dipping part of margin, may be soft-linked via salt detachment to (offset) basement faults
early formation of rollover anticline
downslope thickening of cover sequence
redistribution of salt into footwall roller and hanginowall swell

Figure 5. Cartoons illustrating hard and soft linkage between structures in cover rocks and the underlying basement. Hard linkage occurs where there is no salt interval, or thin salt, separating cover from basement rocks. Soft linkage occurs when a thick salt interval acts as a detachment layer that separates movements in the basement from those in the cover. From Harvey & Stewart (1998).

The right side of Figure 3 shows a number of tectonic events:

- Triassic and early Jurassic rifting is a common feature of many parts of Europe and beyond, for it is linked to crustal extension that drove the break-up of Pangaea. During this rifting episode, and the later one spanning the Late Jurassic to Early Cretaceous, fault movements were contemporaneous with sedimentation, accounting for major lateral thickness changes of stratigraphic units (see below).
- A series of marine shallowing-up successions is shown in the Jurassic, with argillites capped by carbonates, with arenites occurring below some carbonates. The Kimmeridge Clay to Wealden part of the section is the last of these shallowing trends, and at the top includes lacustrine (Purbeck) and fluvial (Wealden) sediments.
- The intra-Cretaceous unconformity was probably associated with uplift to the west associated with rifting that heralded the opening of the Bay of Biscay.
- Tertiary inversion refers to the compressional Earth movements associated with the Alpine orogeny. These caused reversed movement on Mesozoic normal faults along the Jurassic Coast, and associated folding. The folds produced are asymmetric, with steeper, and even overturned, northern limbs.

Structural overview

This section contrasts the tectonic structure of the western part of the Jurassic coast and Lyme Bay with the eastern part and adjacent offshore area from Abbotsbury to Swanage. The western part is characterised by dips of only a few degrees, and by many normal faults, mostly with displacements of a hundred metres or less, and a few showing large movements up to 300 m (left side of Figure 4(a)). To the east, there are three major faults with displacements of 300 to 600 m (Litton Cheney, Abbotsbury-Ridgeway, and Purbeck, see right side of Figure 4(a)). On seismic sections the Purbeck Fault can be traced eastwards beneath the steep northern limb of the Purbeck anticline. To the east, the Abbotsbury Fault truncates the northern limb of the Weymouth anticline. These two anticlines have an *en echelon* relationship to each other as shown on Figure 4(b). Both anticlines are asymmetric with steep northern limbs, which in the case of the Purbeck Anticline is overturned in places.

The role of salt in structural evolution

Harvey & Stewart (1998) showed how differences in the thickness of the interbedded halite and mudstone interval (which they named the Dorset Halite) have influenced the development of different styles of faulting and folding. Where the halite interval is thicker, it acts as a detachment layer, severing linkages between movements in basement rocks (presumed Upper Palaeozoic rocks deformed during the Variscan orogeny, and the overlying Permian and basal Trias) and the overlying Mesozoic rocks. In areas where the halite interval is thin or absent, extension during rifting phases (Figure 3) resulted in normal faults in the basement rocks which propagated into the Mesozoic cover. This relationship is termed 'hard linked' (Figure 5(a)) by Harvey and Stewart (1998), and is exhibited by the Purbeck Fault. Where the halite interval is thicker, the basement faults did not propagate upwards into the Mesozoic cover. Instead, the halite interval stretched and thinned in response to extension, and the overlying sediments were cut by faults as they extended, but these faults did not continue through the halite interval down to the basement. This response to extension is a bit like trying to pull apart a Mars bar that has been

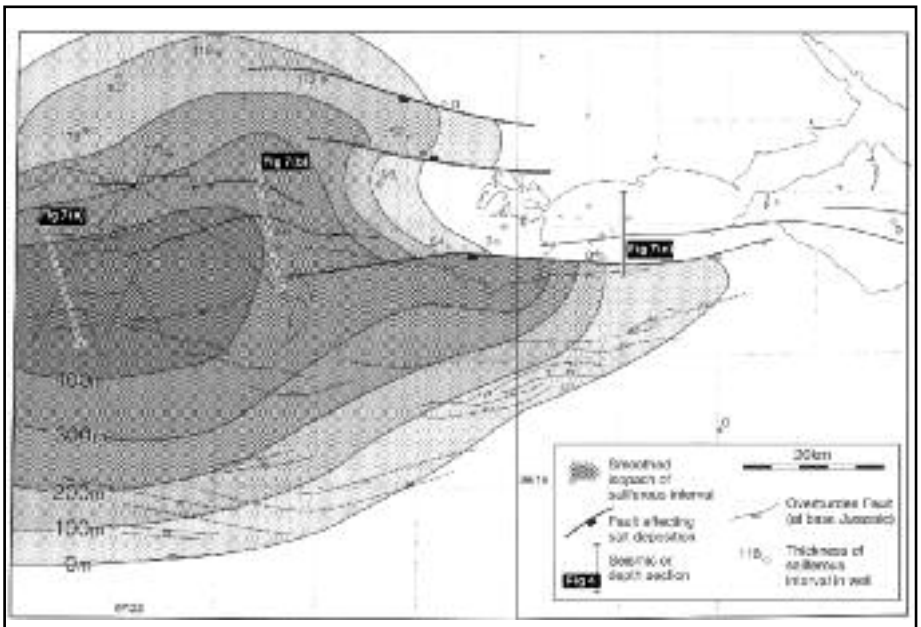

Figure 6. Map showing the thickness of the Dorset Halite interval in the south Dorset and Isle of Wight area. Note that the Purbeck Fault and the Winterbourne-Kingston Graben to the north of it were active during deposition of the saliferous interval. From Harvey & Stewart (1998).

cooled in a fridge for a while. The toffee part (equivalent to the halite interval) responds by stretching, but the chocolate covering (the overlying sediments) is more brittle, so is fractured (analogous to the faults above the halite). This relationship between extension in the basement and faults in the overlying cover rocks is termed 'soft linked' (Figure 5(b)). It occurs in Lyme Bay, and characterises the Abbotsbury-Ridgeway and Litton Cheney Faults.

The concept of hard and soft linkage between extension in the basement and overlying cover rocks can now be applied to an examination of some north-south cross sections based on seismic sections, the locations of which are shown in Figure 6. This figure also shows the thickness of the Dorset halite interval, based on well data.

In Lyme Bay (Figure 7(a)) the normal faults in the rocks above the Triassic salt interval are offset from, and not continuous with, those in the basement, indicating soft linkage between basement and cover rocks. During Tertiary compression, some reverse movement must have occurred along these faults, but not enough to convert them into reverse faults. At Weymouth and to the north (Figure 7(b)) the salt interval detaches the Litton Cheney and Abbotsbury-Ridgeway Faults from the basement indicating soft linkage between movements in the basement and the rocks above the salt. The Litton Cheney and Abbotsbury-Ridgeway faults show listric geometry, flattening downward into the salt layer. Note how the Weymouth anticline only deforms rocks above the salt. It is likely that it originated as a rollover anticline above the Abbotsbury-Ridgeway Fault, and was tightened during Tertiary compression which caused some reverse movement on the fault. The Purbeck Fault cuts through the salt as its displacement is larger than that along the other two faults: this indicates hard linkage between basement and rocks above the salt. Thickening of the Lower, Middle and Upper Jurassic intervals southwards across the faults indicates syn-sedimentary movement. In Bournemouth Bay (Figure 7(c)) all the faults appear to be hard linked to the pre-Triassic basement. Thickening of the Lower, Middle and Upper Jurassic intervals southwards across the faults indicates syn-sedimentary movement. Tertiary inversion is indicated by the folding of the Upper Cretaceous and Tertiary sediments. This is similar to the deformation that occurred along the northern limb of the Purbeck Anticline where the Chalk is overturned in places. Note that reverse movement during inversion along the faults shown in Figure 7(c) was not sufficient to convert them from normal to reverse faults.

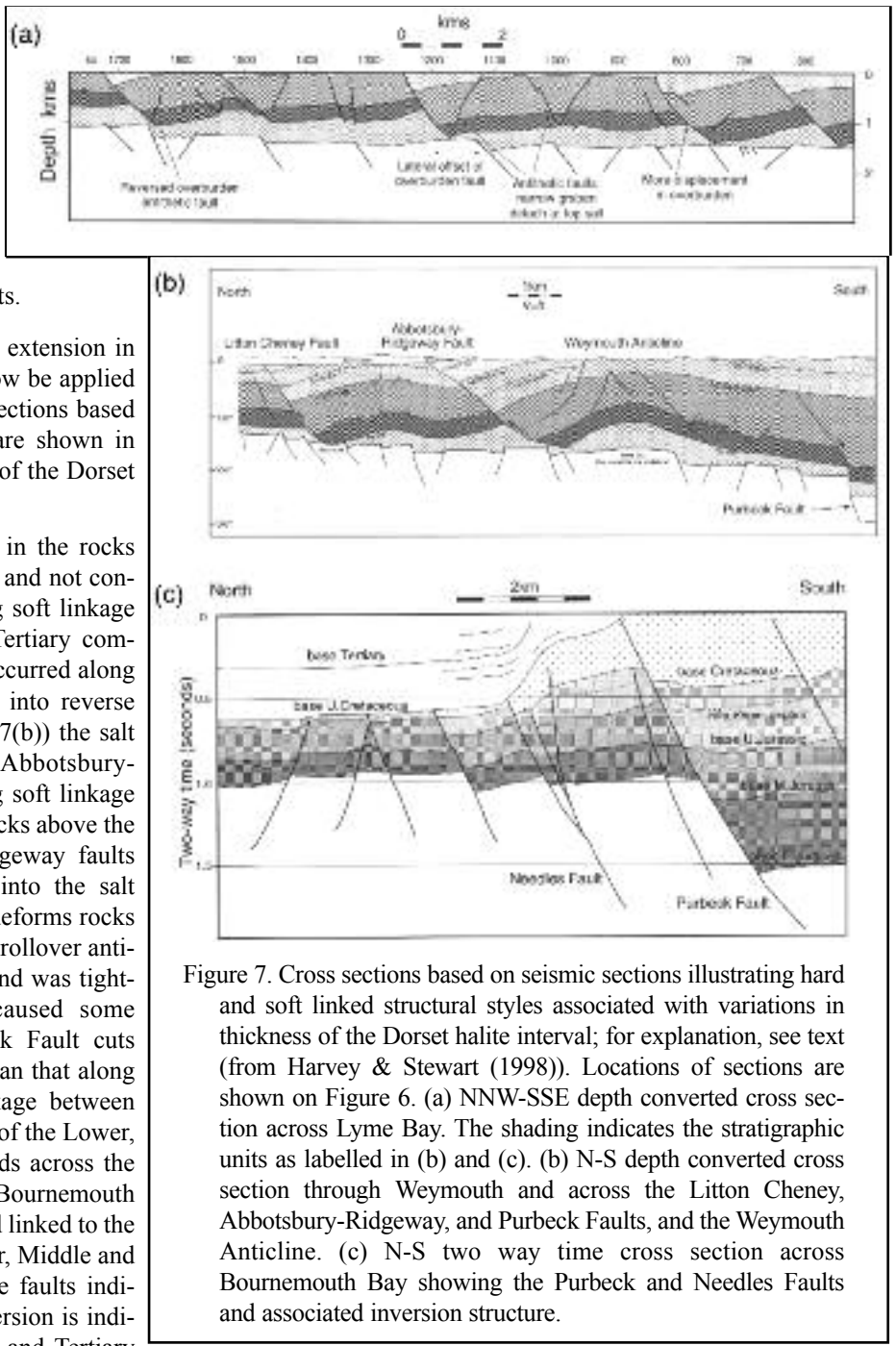

Figure 7. Cross sections based on seismic sections illustrating hard and soft linked structural styles associated with variations in thickness of the Dorset halite interval; for explanation, see text (from Harvey & Stewart (1998)). Locations of sections are shown on Figure 6. (a) NNW-SSE depth converted cross section across Lyme Bay. The shading indicates the stratigraphic units as labelled in (b) and (c). (b) N-S depth converted cross section through Weymouth and across the Litton Cheney, Abbotsbury-Ridgeway, and Purbeck Faults, and the Weymouth Anticline. (c) N-S two way time cross section across Bournemouth Bay showing the Purbeck and Needles Faults and associated inversion structure.

Conclusions

The foregoing information and interpretations form the basis for the answers to the questions posed in the introduction to this paper.

Why is an almost complete record of the 185 million year long Mesozoic Era exposed along the coast of East Devon and Dorset?

The Jurassic Coast is situated within the Wessex Basin which subsided almost continuously during the Mesozoic due to crustal extension resulting in two major rifting episodes (Figure 2) and associated thermal subsidence.

Why do the exposed rocks get progressively younger from west to east?

As the amount of subsidence caused by rifting and subsequent cooling of the crust increased eastwards, the strata became tilted in this direction. Uplift of the Devon and Cornwall area occurred towards the end of the Early Cretaceous prior to the opening of the Bay of Biscay, and during Tertiary compression. Both these events enhanced the eastward tilt of the Mesozoic strata along the Jurassic Coast.

Why are there contrasting structural features displayed in the Lyme Bay and Weymouth Bay – Isle of Purbeck areas (namely many normal faults in the west, and a few large faults and major folding in the east)?

The contrasting structural styles are the result of hard or soft linkage between tectonic movements in the basement rocks beneath the Triassic halite interval. Where the salt is thicker (Figure 6) tec-

tonic movements in the basement do not propagate directly into the cover rocks above the halite interval, resulting in more numerous faults with smaller displacements than those along the major faults to the east. Inversion only caused some slight reduction in the displacement across the normal faults in the Lyme Bay area, whereas in the east, it resulted in the tightening of the Weymouth Anticline that originated as a rollover fault during Mesozoic extension, and folding above the more eastern part of the hard linked Purbeck Fault.

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Earth by Douglas Palmer *et al*, 2003, Dorling Kindersley, 520pp, £30.00 (hardback) ISBN 1405300183.

We're so fortunate these days. Anyone interested in natural history has a wealth of beautiful books to choose from. Is this one special? Yes. indeed it is.

Conceived on a grand scale, this impressive, weighty book reviews all the Earth's major features and environments. As you'd expect from DK. it's a visual treat, packed with approachable text. Beneath the irresistible cover you'll find everything from the Adriatic Sea to the Zagros Mountains, from amber to zebras. There's plenty of wildlife here, and especially habitats, but does the book really put the Earth into perspective? I looked for a sense of deep time. and the notion that it is as important to consider the pollution of Earth's industrial areas, or the effects of tropical deforestation, as it is to revel in the beauty of wilderness. I was not disappointed.

In Victorian times, geologists claimed that 'the present is the key to the past'. Now, Earth scientists say that 'the past is the key to the future'. For example, we can't tell whether carbon dioxide levels in the atmosphere really are exceptionally high today, or predict the effects this will have, unless we know - and understand - what happened long ago. Without studying the fossil record, how could we know that species are probably becoming extinct today at the highest rate since the dinosaurs died out 65 million years ago? And here's a sobering thought: after mass extinctions, some ecosystems - such as reefs - take 10 million years to recover their biodiversity. We desperately need more people to try to understand the way that global systems interact. Thirty - perhaps a hundred - years from now, the relatively few pages in this book devoted to problems such as habitat destruction, the ozone hole, global warming, and water wars could seem - well, inadequate. It's sad that geology is so peripherally taught in schools that the natural fascination children have with dinosaurs, volcanoes and crystals can usually only develop outside the classroom. Let's hope this book will help to turn on a new generation to Earth Science. It's a bargain at £30. and this time the cliche is true: every home should have one.

Peter Sheldon, Senior Lecturer in Earth Sciences, the Open University. This review originally appeared in BBC Wildlife Magazine. March 2004.

Life's Solution: inevitable humans in a lonely Universe by Simon Conway Morris, 2003, Cambridge University Press 464 pages, £18.95 (hardback) ISBN 0521827043.

Stephen Jay Gould famously wrote in *Wonderful Life* when describing the amazing fossils of the Burgess shales that if the tape of life were to be re-wound and played again, the chances that the same out-comes would be arrived at would be so remote as to be considered to be nil. This book by Simon Conway Morris whilst admitting that the chances that the re-running of the tape would produce ourselves again is fairly remote, challenges this view of the way the forces that that govern life operate: what about the underlying principals of life? Rather than accepting that the atoms/molecules that first coalesced to produce life from the primordial soup did so by pure happenstance, he suggest that there is an underlying control of what is practicable, i.e. there are only certain pathways for nature to follow that could produce life and once these are embarked upon would lead to us or at least something similar.

To support this view the author calls upon "evolutionary convergence": the recurrence within the record of life preserved in fossils from the dawn of time and through the ages of biological organizations to arrive at the same solution to a problem. He highlights this view with numerous examples, the most famous perhaps being the evolution of camera-like eyes in the octopus and those of all vertebrates (this way of seeing the world has arisen at least six times according to the fossil record). Although once life has started its journey through the seas of time, it may be charted with a good idea of where it will make landfall, the chances that it may have to start the journey at all might be small. For life to get going, the planet on which it starts needs to be just right and as we look out ever further into the universe we seem to find that perhaps the Earth is really a very special place and indeed we might be alone.

The book itself is well set out introducing the reader to each example of evolutionary convergence with a thoughtful approach that carries them along without becoming to confused in detail but rather allows them to see the greater theme the author wishes to convey, with each chapter building on the preceding ones. For each chapter there are copious footnotes to which a reader may refer at the end of the book with a comprehensive index beyond this as well.

Chris Gleeson BSc Hons (Open) Nat Sci

Some aspects of the Geomorphology of the Dorset and East Devon World Heritage Site

John Chaffey, Earth Sciences Author and Chairman of the Dorset Geologists' Association Group

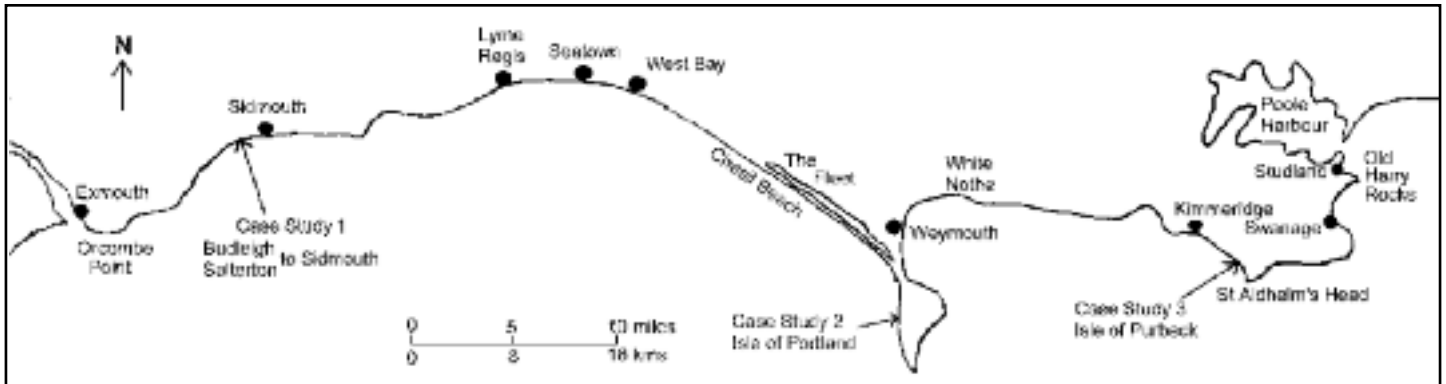

Figure 1. The Dorset and East Devon Coast World Heritage Site.

The World Heritage Site of the Dorset and East Devon Coast displays some of the most spectacular landforms in Europe. It extends for 155km (95 miles) from Orcombe Point, near Exmouth in the west to South Beach, Studland in the east (Figure 1). The extraordinary variety in its cliffs and beaches is due in no small measure to the very considerable range of rocks that outcrop along this coast. As the rocks possess, in general, a gentle dip to the east, there is an almost continuous exposure of the strata of the Mesozoic from Lower Triassic in the west to Upper Cretaceous in the east (185 million years of geological time). The forces of marine erosion, acting on these exposures, have sculpted a suite of coastal landforms that reflect the varying lithologies and structures displayed along this coast.

Geological Background

In the west the Triassic rocks consist principally of sandstones, conglomerates and mudstones, their red colour reflecting their desert origin. Everywhere they form strong, rocky cliffs of varying magnitude, although to the east of Straight Point the section of cliff known as The Floors shows some evidence of instability-induced landslides in the Aylesbeare Mudstones. From High Peak eastwards, the capping of Cretaceous rocks above the overstepping unconformity, adds its own distinctive element to the cliff morphology.

Although the Cretaceous makes an appearance to form the whole of the cliff face at Beer Head, it is the Jurassic strata that dominate the coastline of West and South Dorset from Lyme Regis to White Nothe, where the Chalk makes its reappearance to form almost the whole of the cliff face. Lower Jurassic, or Liassic rocks form all or part of the cliffs from Lyme Regis in the west to Burton Bradstock, in the east, with the ubiquitous Cretaceous rocks again forming an important capping from Black Ven eastwards to Abbotsbury Castle. The Lower Lias, which form the lowest part of the Jurassic sequence are mainly mudstones, with interbedded thin limestones and sandstones. It forms inherently unstable cliffs whose faces are scarred by landslides, particularly in the section between Lyme Regis and Golden Cap. Sandy horizons play an increasingly important part in the Middle and Upper Lias, culminating in the distinctive Bridport Sands which form the spectacular, almost vertical cliffs, between West Bay and Burton Hive (Figure 2).

Figure 2. Upper Lias, Bridport Sands, Burton Cliff.

Although important stratigraphically, Middle Jurassic rocks only occur along the main coast intermittently, just to the west of West Bay, and to the east of Burton Bradstock. Their most important outcrops are found along the inner shore of The Fleet, where they now have little impact on cliff formation, since the waves generated in the sheltered waters of The Fleet have little erosive power.

Upper Jurassic rocks are responsible for some of the outstanding cliff landforms of the Heritage Site. The Oxford and Kimmeridge Clays often form unstable cliffs, although the Kimmeridge Clay cliffs to the east and west of Kimmeridge itself give rise to vertical cliffs in the shales stiffened by cementstones. It is the much stronger, resistant rocks of the Portland Group in particular, which give rise to the prominent cliffs of the Isle of Portland and the southern coast of the Isle of Purbeck between St. Aldhelm's Head and Durlston Head. Corallian strata also give rise to robust cliff sections to the west of Ringstead.

Cretaceous rocks, apart from the cliff-top cappings in Devon and West Dorset and the spectacular cliffs at Beer Head and Hooken in East Devon, make their main contribution to cliff scenery in East Dorset east of White Nothe. As a result of the involvement of the rocks and the Chalk, in particular, in the Alpine earth movements, the strata are often highly dipping or even vertical; a clear contrast with the gentle dips in the Triassic and Jurassic strata in East Devon and West Dorset. High, near-vertical cliffs in steeply

dipping Chalk appear both to the west and east of Lulworth and in the cliff sections immediately to the north of Swanage, although dips lessen on the northern side of the Ballard Fault as Old Harry Rocks are approached. By way of contrast, the clays, marls, grits and sandstones of the Wealden Beds form unstable cliffs in both Worbarrow and Swanage Bays in the Isle of Purbeck.

The Evolution of the Coast

A very simple view of the macro-geomorphological features of the Heritage Coast might be seen as three main bays, Lyme Bay, Weymouth Bay and Poole Bay, separated by the Isle of Portland, with its tombolo connection to the mainland, and the Isle of Purbeck. Thus Lyme Bay has been eroded in relatively unresistant Triassic and Lower and Middle Jurassic rocks, Weymouth Bay has been eroded in the Middle Jurassic rocks and Poole Bay in the Tertiaries. The intervening features of the Isle of Portland and the Isle of Purbeck are fashioned from the much tougher Portland Limestones. It is difficult to put any time scale on the formation of these macro-features of the coast, although it is likely that most of these broad outlines of the coast were in place before the onset of the Pleistocene.

The evidence for past sea-levels along the Heritage Coast is scant enough. We do, of course, have the raised beaches at Portland, which suggest sea-levels on the western raised beach of 15 - 16m above mean sea-level (approximately 210,000 BP), and on the eastern raised beach 7 - 10.75m above present sea-level (approximately 120,000 BP) (Goudie & Brunsden 1997). Evidence for similar features and thus higher sea-levels elsewhere along the coast is difficult to find. Suggestions have been made of possible sites at Lulworth and along the south coast of the Isle of Purbeck, although detailed research has yet to confirm this. There are also possible old cliff lines behind Burton Mere just to the west of West Bexington and again behind Kimmeridge along the face of the Portland Limestone escarpment.

There is evidence for past periglacial activity at a number of locations along the coast. Important periglacial screes are found at the foot of the cliffs along the northern side of the Isle of Portland, at the foot of St. Aldhelm's Head and beneath White Nothe.

Where cross profiles of valleys are exposed along the coast, as at Scratchy Bottom to the west of Durdle Door, thick infillings of periglacial material (Head) are exposed.

It is therefore entirely possible that many of the cliff features of the present coastline may be quite old, and contemporary wave action is merely trimming up features of some antiquity.

Contemporary wave attack on the Heritage Coast will certainly be affected by the degree of fetch or exposure to prolonged wave attack. Much of the eastern side of Lyme Bay is open to wave attack with a fetch extending well down the Channel and beyond, some say to the South American continent. Weymouth Bay is relatively sheltered by the mass of the Isle of Portland, but exposure increases again as the Isle of Purbeck is approached. South-easterly fetch is significant in the western parts of Weymouth Bay and along the eastern side of the Isle of Purbeck, and becomes progressively more important the farther west one moves along Lyme Bay.

The Landforms of the World Heritage Site

It is possible to recognize three main elements in the suite of landforms that are displayed along the coast of the World Heritage Site. Cliffs are the dominant landform, occupying more than sixty percent of the coast. Inevitably they vary greatly in their form under the influence of lithology, structure, exposure and relief of the landmass in which they are cut. Many of the cliffs particularly in West Dorset, but also at other sites in East Devon and East Dorset, are complicated by landslides which are a second major element in the landforms suite. The third element in the landforms suite are the beaches of the Heritage Coast. These vary from the vast stretch of Chesil Beach to the many smaller beaches that are found in East Devon and West Dorset and in South and East Dorset. The link between the three is obvious enough. Erosion of the cliffs, and landslide supply of debris down–cliff, will supply beaches with renewing elements in their make-up. Beach material can move along the shore or normal to the shore. It can be used as a tool of wave attack in corrosive activity and can also have an attritional function. Beaches do also have an important role in protecting the base of cliffs from erosion.

Cliffs

Along a coastline of 155km there is such a bewildering variety of cliff forms that they almost defy classification. However, some broad categories may be determined :

1) Vertical cliffs, with varying degrees of development of a talus slope at their base, dependent upon supply of debris from the cliffs and the ease with which it is removed by wave action: much of the East Devon coast between Otterton Ledge and Ladram Bay falls into this category.

2) Vertical cliffs plunging straight into steep water: relatively rare but examples along the south–west coast of the Isle of Portland, Chalk cliffs between Ballard Point and Old Harry Rocks.

3) Cliffs affected by large scale landslides: these are common in West Dorset: Black Ven, Stonebarrow Hill; in East Devon, the Hooken landslide, the Axmouth–Lyme Regis Undercliff; White Nothe in East Dorset; Houns-tout, Emmetts Hill and St. Aldhelm's Head in the Isle of Purbeck.

4) Clay cliffs, often with some slumping: the cliffs from Redcliff Point to Osmington Mills in South Dorset, Burton Hive cliffs in West Dorset, Worbarrow Bay and Swanage Bay in the Isle of Purbeck.

5) Slope and wall cliffs: the south coast of the Isle of Purbeck, where Purbeck Beds, often with periglacial cover, form the slope leading down to the wall of Portland Limestone plunging sheer into deep water.

Landslides

Landslides are a common feature along much of the Heritage Coast. In the East Devon section, the most celebrated example is that at Hooken. In 1790 a mass of Chalk and Upper Greensand (1300m long and 250m wide) weighing about 8 million tons foundered and slipped seawards. The failed horizon appears to have been a thin seam of clay at the base of the Upper Greensand. The seabed was raised up to 5m in the air (complete with lobster and crab pots that had been placed in position the previous night). Today the offshore remnants of this slide are seen in Sherborne Rocks. Towering above the beach are The Pinnacles, the landward remains of this landslide (Figure 3). At the time fragments of hedgerows and even a stile remained undisturbed on the slipped mass. Today it is still possible to match up the flint bands and the

Figure 3. The Pinnacles and Under Hooken.

'hardgrounds' in the Pinnacles with the equivalent levels in Hooken Cliff (Gallois 2004).

Further to the east is the classic landslide complex between Axmouth and Lyme Regis, extending for about 8km east-west along the coast. The zone of instability is some 500m wide and over 200m high. The famous Bindon landslide occurred on Christmas Eve, 1839. A slice of land, Goat Island, moved seawards, leaving a 'Chasm' 200m wide, 30m deep and 1.5km long. (Brunsden 2000). Both William Conybeare and William Buckland were in the area at the time and together wrote a report, the first real scientific analysis of a landslide. They correctly identified the role of downward percolating water in causing 'the lower region of the Foxmould (the lowest layers of the Upper Greensand) to become so highly saturated with water as to reduce to semifluid quicksand.' (Buckland 1840). Two coastguards witnessed these events at close quarters and fled across fields riven with fresh deep cracks; they probably considered themselves lucky to escape with their lives.

The Black Ven landslide complex is one of the largest mudslide systems in Europe (Koh 1992). On Black Ven, Lower Liassic mudstones are overlain by Upper Greensand. Rotational slides affecting the Upper Greensand appear to result from the weakness of the lowest layers of the Foxmould at the base of the Upper Greensand which fail when they become saturated. Below the Upper Greensand cliffs, saturated debris will move across benches in the Liassic shales and marls and will eventually be funnelled into major mudslides that cut across the terraces in the lower parts of the cliff. At the foot of the cliffs at Black Ven the mudslides merge into broad lobes that extend out into the sea.

Stonebarrow Hill to the east is the site of another important landslide complex. Although the geology is broadly similar to Black Ven towards the west, dips have now carried the Black Ven Marls down to sea-level and the main sea cliff is formed of the Belemnite Marls, which on Black Ven are much higher up the cliff complex. Three main zones are recognised on Stonebarrow Hill (Brunsden and Jones 1976). The highest zone is developed on the Cretaceous deposits (Upper Greensand and Gault) and is characterised by rotational slides. Beneath is a zone in Middle Liassic rocks with small rotational slides, mudslides, mudflows and slumps. The lowest zone consists of 40m to 60m of sea cliffs; mudslide debris spills over their crest and often pulls away the upper part of the cliff.

The Isle of Portland is also affected by landslides; some 27% of its area has been shown to be landslide prone. Portland Stone overlies Portland Sand, which in its turn is underlain by Kimmeridge Clay. Water cannot percolate through the Kimmeridge Clay which is eventually squeezed out, causing landslides. The nature of the landslides varies in different parts of the Isle. In the north both West Weares and East Weares are affected by deep-seated rotational slides. In the eastern parts of the island, a down-dip situation means that the rocks founder or topple, producing a fundamentally different cliff form(Brunsden *et al.* 1996).

East Dorset also displays important landslide phenomena at locations such as White Nothe, Worbarrow Bay, Gad Cliff, Hounstout and St. Aldhelm's Head. Most of these landslides are deep-seated and very old and do not appear to have been re-activated by the post-glacial rise in sea level. These landslides have not attracted much research attention, compared to the West Dorset examples and thus, little is known about them.

Figure 4. Chesil Cove and Chesil Beach.

Beaches

Pocket beaches characterise most of the Heritage Coastline from Orcombe Point to West Bay in East Devon and West Dorset, and again between Weymouth and Old Harry Rocks in East Dorset. Most of the material on the beaches is either flint or chert derived from the Jurassic and Cretaceous rocks that outcrop in the cliffs. However, in the west, the outcrop of the Triassic Budleigh Salterton Pebble Beds yields a supply of the distinctive quartzite pebbles that occur in these beds. The quartzite pebbles are an important component of the beaches in East Devon, but they are also found in the beaches to the east, suggesting that there was longshore drift available to move them eastwards at times of lower sea-level in the past.

Between the two areas of relatively small pocket beaches lies the magnificent shingle structure of Chesil Beach (Figure 4). It extends from Chiswell at the northern end of the Isle of Portland westwards to what may be regarded as an arbitary limit in the west. Suggestions for a western limit vary from Abbotsbury, West Bay, Eype Mouth or even Golden Cap. If we regard West Bay as the western limit, the beach extends for 28km from north-west to south-east. For 13km of that distance it is backed on the landward side by the shallow lagoon of the Fleet. Chesil Beach is widest opposite The Fleet (150 – 200m wide) but much narrower adjacent to the cliffs to the west. The height of the beach increases from 7m at Abbotsbury to 14m at Chiswell. Ninetyfive percent of the material of the beach consists of flint or chert, derived from a number of sources, with also Triassic quartzite clasts from Budleigh Salterton. The beach is famous for its grading of mate-

rial, from pea size at Abbotsbury to cobble size at Chiswell, although to the west of West Bexington the pattern is perhaps less clear.

Pebble thickness seems to be the major factor affecting the movement of pebbles. Movement does appear to be mainly to the east, but this is not always the case. The largest waves probably move the largest pebbles to the east, with a westerly movement of smaller material being the result of smaller waves.

The original gravel source for the beach was fluvial/periglacial material on the floor of Lyme Bay, gradually decreasing in amount as the post-glacial rise in sea-level slowed down. Subsequent erosion on cliffs to the west supplied flint and chert, but this source appears to have been cut off when the piers at West Bay were built in the mid 1860s. The beach appears to have gradually been driven onshore: the evidence for this is derived partly from historical maps and charts, and partly from the occurrence of peaty material on the seaward side of the Beach which originally accumulated in a'proto-Fleet'.

Various theories have been put forward to account for the unique nature of Chesil Beach. One idea conceived Chesil Beach as growing out as a spit supplied with material from the west, until it eventually linked Portland to the mainland in the form of a tombolo. Another hypothesis suggests that there was once a 'great beach' offshore, along which pebbles moved freely. This beach would have been gradually pushed onshore during the post-glacial rise in sea-level, incorporating gravel spreads on the floor of Lyme Bay, and building steadily as the whole structure moved towards the north-east. It is suggested that between 5000-4000 BP Chesil Beach may well have occupied a position slightly seaward of its present one. Between 4000-2000 BP tidal conditions may have developed within The Fleet through Small Mouth when The Fleet opened up to the forunner of Weymouth Bay and there was a continuous beach between Portland and Abbotsbury. A separate beach faced east into Weymouth Bay. Marine erosion to the west released large volumes of material to allow the beach to grow to its current form. In historical time the building of both the Cobb at Lyme Regis and the Bridport Harbour piers meant that the supply of material from the west was cut off. Thus Chesil Beach is perhaps at present a relict feature suffering from a slow decline in volume. It would appear that its development can be regarded as occurring in two phases: an earlier sand and gravel feature on which a more massive structure of cobbles was built as the material became available (May 2003).

The Fleet, behind Chesil Beach, is a tidal lagoon, 480ha in area. It varies from 50m to over 900m in width and is generally a shallow feature. There is a relatively small discharge from landward streams into The Fleet but there is a large volume of water at low tide. However, the tidal flow is much restricted by the very narrow tidal inlet at Smallmouth. Physical conditions within The Fleet mean that it has a particularly rich flora and fauna, with distinctive differences between the eastern narrow section and the much more open truly lagoonal section to the west.

The Case Studies

Three case studies used to illustrate different aspects of the Dorset and East Devon Heritage Coast are :

- Budleigh Salterton to Sidmouth
- The Isle of Portland
- The Isle of Purbeck (the Lulworth Coast and Houns-tout to St. Aldhelm's Head)

The stretch of the Heritage Coast between Budleigh Salterton and Sidmouth has been chosen because it illustrates some of the salient features of the Triassic coast in the west, particularly the spectacular Ladram Bay. The Isle of Portland acts almost as a fulcrum for the Heritage Coast, with the coasts of Lyme Bay to the west and Weymouth Bay and the Isle of Purbeck to the east. Its simple limestone block structure, and its landslide-prone cliffs give it a unique place in the geomorphological variety of the Heritage Coast. In the east, the Isle of Purbeck probably offers a greater variety of coastal landforms than any other part of the Heritage Coast. Not only does it offer the relatively close juxtaposition of concordant and discordant coastlines but within these coastlines there is much of geomorphological interest particularly the evolutionary sequence of landforms in the Bat's Head – Worbarrow Bay stretch of the concordant section.

Budleigh Salterton to Sidmouth

There are two main features of interest in this section of the Heritage Coast: Budleigh Salterton Beach and cliffs and Ladram Bay. Budleigh Salterton Beach stretches between the two enclosing headlands, Straight Point in the west and Otterton Point in the east. Littleham Cove in the west is overlooked by cliffs cut in the Aylesbeare Mudstone, which rise eastwards to the highest point at West Down Beacon, where the Budleigh Salterton Pebble Beds first appear in the upper part of the cliff. Landslides below West Down Beacon yield sand, clays and pebbles for the beach below. Farther to the east cliffs cut in the Budleigh Salterton Pebble Beds and the Otter Sandstone are affected by rockfalls. The beach has an almost zeta-type* form in Littleham Cove, and extends eastwards to Budleigh Salterton, continuing as a barrier beach, resting on the terraces of the Otter Valley, and eventually assumes the form of a spit across the mouth of the Otter. The beach is well known for the distinctive quartzite pebbles, derived from the Budleigh Salterton Pebble Beds, that are almost its sole constituent. The beach is orientated towards the south-south-east, and wave energy is somewhat reduced as a result of the refraction of the dominant southwest waves. There is little need for coastal defence protection at Budleigh Salterton, an indication of the overall stability of the beach. It is thus an intact natural system, anchored at the enclosing headlands and resting on the cliff foot. It is virtually unmodified (May 2003).

Ladram Bay, with its well-developed cliffs, stacks and platforms cut in Triassic sandstone, is one of the Heritage Coast's most unusual and spectacular sites (Figure 5). Its stacks are almost without parallel on the south coast and owe their persistent form to the fact that this is a low energy site. The platforms are controlled by the almost horizontal bedding planes of the resistant bands that crop out at sea-level here. Erosion along the vertical joints has clearly aided the isolation of the stacks. The stacks beneath High Peak, and those immediately north of Ladram Bay exist and survive as a result of a series of local factors: local structural weaknesses and a wave climate sufficient to exploit these weaknesses and, most importantly, the existence of a resistant band at the base of the stacks. It is the presence of these tougher pedestal-forming beds that leads to stack formation in what are relatively weak sandstone strata (May 2003).

* Zeta form beaches are formed when a series of headlands partially block long-shore transport.

Figure 5. High Peak and sea stacks near Ladram Bay.

The Isle of Portland

The Isle of Portland extends in a north-south direction for about 6km and is approximately 2.5km from west to east. The surface of Portland slopes from 150m at the northern end to about 6m near Portland Bill. It is surrounded by cliffs, precipitous on the west with almost vertical walls rising above narrow debris slopes below. High cliffs are also characteristic of the eastern side of the Isle with a much wider debris slope below. In the south-west high cliffs drop sheer into deep water, but in the south-east the cliffs are much quarried (Brunsden *et al.* 1996). The Isle of Portland is usually regarded as lying on the southern limb of the asymmetrical Weymouth Anticline, with dips mostly in the range 1.5° to 2.5° slightly east of south. It is thought however that the orientation and dip of the rocks on Portland is closely related to the existence of the Shambles Syncline to the south-east of the island. This is a complementary structure to the main Weymouth Anticline. The joint system of the rocks on the Isle of Portland, orientated from NNE to SSW is also related to the trend of the Shambles Syncline.

The key formation on the Isle of Portland is the Portland Stone, a series of massive limestones overlain by a veneer of Lower Purbeck Beds. It rests on the Portland Sand and the Kimmeridge Clay, both of which are much less competent than the Portland Stone. The sequence of rocks thus described indicates almost ideal conditions for the development of landslides. Water percolates down through the permeable limestones to the impermeable beds below, building up high pore pressures and generally destabilising them. There are a number of potential failure surfaces within the Kimmeridge strata.

Some 27% of Portland is affected by landslides including most of the coastline with the exception of the south-east from Freshwater Bay southwards to Portland Bill where structural conditions are not so favourable. Landslides clearly affect both property and communications and have been a constant threat to human occupation of the Isle. Some of the older landslides are relatively stable and Chiswell itself is built on such a feature. The old Portland to Weymouth railway which followed a course along the north-east coast of Portland was often closed by landslides. More recently the main road linking Tophill with Underhill was often affected by cracking at Priory Corner until it was completely re-aligned in 1996. Some of the most threatening landslides occur on the northern end of the Isle of Portland where conditions are most favourable for their development. Here, at West Weare and sites overlooking the former dockyard at Castletown and Balaclava Bay, the island reaches its highest elevation and there is maximum exposure of the unstable Kimmeridge Clay, there is deep water offshore and an anti-dip orientation (Goudie & Brunsden 1997). As a result, massive deep-seated rotational slides occur in this area. Varying structural and groundwater conditions govern landslide development elsewhere.

Portland's two raised beaches are also of considerable geomorphological interest. The western one, close to a former Ministry of Defence establishment, displays a clear section of a variety of materials overlying the cobbles of the beach itself. Periglacial head material, with characteristic congeliturbation and a shelly fauna suggest sub-Arctic conditions. Beneath is a fine loamy deposit which is probably a brackish coastal lagoon deposit. The beach itself consists of pebbles overlying much larger limestone boulders which show typical imbricate structure.

On the eastern side of the southern part of the Isle of Portland is the lower raised beach. Beneath the beach itself there are relict features that suggest colder conditions that may have preceded the interglacial during which the beach was laid down. The shore platform here is heaved and cracked, together with evidence of some possible patterned ground. (Goudie & Brunsden 1997)

The Isle of Purbeck

For an area with a relatively short coastline, the Isle of Purbeck shows very considerable variety in its geomorphological features. Broadly speaking, its concordant coastline runs from Bat's Head in the west to Durlston Head in the east.

The discordant coastline extends from Durlston Head northwards to the northern limit of the World Heritage Site at South Beach Studland where the Chalk gives way to the younger rocks of the Tertiary Period. It is proposed to examine briefly the main features of two sections of the concordant coastline: the section from Bat's Head to Worbarrow Bay, and the smaller stretch from Houns-tout to St. Aldhelm's Head.

The coast around Lulworth Cove is probably the most intensively studied section of the British coastline. It is said that the various stages in the development of the concordant coastline can be examined in this section. A series of coves and bays from Durdle Cove in the west to the much larger Worbarrow Bay in the east may be regarded as showing different stages in the erosional development of the coast. Stair Hole, with its caves breaching the Portland Limestone barrier and an incipient cove developing behind in the Purbeck and Wealden Beds, has been regarded as demonstrating the earliest stage of development. Lulworth Cove, with its near perfect outline, could represent an intermediate stage. Mupe Bay, Worbarrow Bay and Durdle Cove could represent a later stage where bays may have merged with one another.

Such a simplistic model has been challenged recently. The geological conditions are not completely similar along this coast since the parallel Jurassic and Cretaceous beds widen in outcrop towards the east. It would appear also that the well-developed system of valleys along this coast may have had an important role to play. In particular the valley system that focuses on Lulworth Cove may well have extended farther seawards and this would obviate the need for marine erosion to cut the gap at the entrance to Lulworth Cove. Stair Hole is much smaller and does not have a valley system leading down towards it and clearly has a different origin to Lulworth Cove (Goudie & Brunsden 1997). Valley systems to the west of Lulworth Cove may have had some influ-

ence on the evolution of the coastline between Durdle Door and Bat's Head, and a similar influence may be postulated for the development of Worbarrow Bay.

Whereas the rocks in the Bat's Head-Worbarrow Bay section are steeply dipping towards the north, the strata in the Houns-tout – St. Aldhelm's Head section have very gentle dips, resulting in a different landform association. The sequence of Portland Limestone overlying Portland Sand and Kimmeridge Clay is similar to that of the Isle of Portland, and thus landslides are a prominent feature of this section. However, the tumbled undercliffs that lie below Houns-tout, Emmetts Hill and St. Aldhelm's Head appear to be the result of landslides of considerable age. There are some areas of current landslide activity but these are essentially localised as at the western end of Chapman's Pool (May 2003).

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Book reviews

The Geology of Ireland edited by Charles Hepworth Holland, Dunedin Academic Press, Edinburgh, 2001, 531pp, £85.00 hardback (Ireland €125.00), £55 paperback (Ireland €81.40) ISBN 1903765048 hardback, ISBN 1 903765 07 2 paperback.

The Geology of Ireland is a nicely presented book with an attractive full colour cover. It is a very full account of all aspects of the geology of Ireland. It is generally well written though style and readability vary throughout because there are contributions by a variety of experts. This is a book for the serious student of Irish geology.

Following the Introduction, the chapters generally follow a time line. The Precambrian (Chapter 2) introduces us to the oldest rocks in Ireland the Pre-Grampian orthogneisses from Inishtrahull in Donegal and the Annagh Gneiss Complex in north Mayo and so it continues through to Chapter 17, the post-Glacial sediments of the last 10,000 years. There are a couple of diversions with chapters on geophysics (Chapter 15) and offshore Ireland (Chapter 18). The final chapter (Chapter 19), on the History of Irish Geology, is by Gordon Herries Davies, who some of you may remember gave a superb talk on that very subject during the 2001 OUGS Symposium Dinner in Dublin. Each chapter is clearly defined in its remit e.g. Cambrian of Leinster, Caledonian Deformation, Permian and Mesozoic, and each is written by up to three experts on that branch of Irish geology. The layout is in two tightly printed columns with plenty of black and white illustrations. The photographs are mostly excellent in their choice and coverage. However, many of the diagrams are rather heavily ornamented and some have been reduced too much making them difficult to read. The captions for the figures are in a small point size.

The Geology of Ireland follows on from an earlier book A Geology of Ireland (1981) also edited by Holland, a former Professor of Geology in Trinity College, Dublin. In The Geology of Ireland there are comprehensive reference lists provided at the end of each chapter. This is a great improvement on the earlier book which contained only selected references, a shortcoming acknowledged by the editor. This is a book crammed with information about Ireland's geology. It is not the easiest book to read and you may well need pencil and paper to take notes. It is a heavy book in both senses of the word, weighing in at over 1.5kg (!) but it is also a quality book.

Susan Pyne, MSc, BA Hons (Open)

Meteorites, Ice, and Antarctica by William A Cassidy, Cambridge University Press, 2003, 349pp, £19.95 hardback, ISBN 0521258723

The tenor of much of this book is portrayed on the dust jacket. Dressed in antarctic gear with icicles protruding walrus tusk-like from moustache and beard, the portrait of the author says much about the arduous nature of rock collecting in a land where anemometers register 200 km/hr before being blown away.

This is a personal account of a remarkably successful project, which resulted in the collecting of over 30,000 meteorites including several specimens with origins on the moon and Mars. It is also an example of serendipity, where the discovery of four distinctly different stony meteorites within a relatively small area of ice sparked off a quest to find a mechanism that would explain such unprecedented concentrations. The early pages deal with the politics of obtaining clearance for research proposals and working with other interested groups as well as the logistics of getting to and surviving at remote sites. An important factor favouring the accumulation of meteorites is the dry deep-freeze conditions in Antarctica where weathering is very slow and therefore meteorites can survive on the ice for very long periods. The concentration of meteorites in specific areas is convincingly explained by a complex interaction of microclimate, ice movement, rock barriers and sublimation of the snow and ice cover.

The occasionally wordy nature of some chapters is relieved by anecdotes and humour. Such as the closeness of Scott's route to the South Pole to a major concentration of stranded meteorites and the most important vertebrate fossil site in Antarctica; also the Antarctic method of making a limited number of sets of underwear last the whole season without washing There is much in this book for both the specialist and the general reader. I learnt a great deal, not the least of which was a clearer appreciation of the evidence for the attribution of a number of specimens to the moon and Mars. If I had a criticism it would be that the non-specialist reader would have benefited if chapter 8, which deals with origins and classification, had been placed earlier in the book. Also the inclusion of a table (similar to that provided in S267 Block 1 p46) would have clarified the relationship between metamorphic grade and iron oxidation state in the classification of chondrites. The book is a must for anyone interested in the geological aspects of planetary science.

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Red rocks of the west - the tip of the 'iceberg'

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The Dorset and East Devon Coast World Heritage Site (the 'WHS') is popularly known as the 'Jurassic Coast' but includes exposures of both younger, Cretaceous, and older, Triassic, rocks. The latter, the 'red rocks of the west' that are the subject of this contribution, are seen in the east Devon part of the WHS where they are exposed almost continuously for nearly 37km, between the east side of Pinhay Bay, near Lyme Regis, and the western end of the WHS, at Orcombe Point, near Exmouth. This part of the WHS may, justifiably, be termed the 'Triassic Coast'. The position of the base of the Trias is poorly constrained in this area however, and the 'red rocks', largely of Permian age, that are exposed west of the WHS for some 25km between Exmouth and Torbay, are included in this contribution. The succession seen in the 'tip of the iceberg' between Torbay and Pinhay Bay extends, with some variations, eastwards at subcrop beneath Jurassic and younger rocks in east Devon, Dorset and contiguous counties, and offshore (Hamblin *et al*. 1992; see in Underhill 1998). A British Geological Survey memoir on the geology of south Dorset and the WHS is in preparation (Barton *et al*.).

The exposed succession

This comprises Permian and Triassic rocks that dip gently eastwards beneath an unconformable and highly dissected cover of Cretaceous rocks; older units are seen in the west and younger ones appear successively to the east. From west to east the succession comprises formations that constitute the Exeter, Aylesbeare Mudstone, Sherwood Sandstone, Mercia Mudstone and Penarth Groups, and the basal part of the Lias Group; it spans around 95 million years.

The **Exeter Group** rests unconformably upon Devonian and Carboniferous rocks affected by the Variscan Orogeny. An unconformity, representing up to 15 million years of erosion and non-deposition, separates formations of the lower and upper parts of the group (Edwards *et al*. 1997; Edwards & Scrivener 1999; Leveridge *et al*. 2003). These formations are of continental origin and consist largely of conglomerates and coarse sandstones that become finer-grained eastwards and which formed on large subaerial alluvial fans sourced from uplands to the west. The group varies considerably in thickness, with up to 600m seen on the coast and over 1100m inland, to the north-west of Exeter.

The lower part of the group includes the **Exeter Volcanic Rocks**, eroded vestiges of once extensive flows of basaltic and lamprophyric lavas that have yielded isotopic evidence of an Early Permian, Asselian to Artinskian, age (Edwards *et al.* 1997; Edwards & Scrivener 1999). Fossils are restricted to scarce burrows (*Beaconites*) which are not indicative of age but record the presence of an animal adapted to harsh conditions, and imply the existence of other biota in a food chain of which no other trace has yet been recovered.

The upper part of the group lacks volcanics. However, the lower formations have yielded fossil conifer pollen (Warrington & Scrivener 1990; Edwards & Scrivener 1999) that indicate a maximum age of Wordian (Mid Permian). The **Dawlish Sandstone Formation**, near the top of the group, includes substantial aeolian sand dune and interdune deposits formed under the influence of north-westerly directed winds (Laming 1966; Selwood *et al.*1984; Edwards & Scrivener 1999; Newell 2001). Vertebrate tracks (*Chelichnus*) from this formation (Warrington & Scrivener, 1990) record a land fauna and imply the existence of a food chain of which no other components have yet been recovered.

The **Aylesbeare Mudstone Group** crops out on the east side of the Exe estuary and is the lowest 'red rock' unit in the WHS. It rests unconformably upon the Exeter Group and comprises the **Exmouth Mudstone and Sandstone** and overlying **Littleham Mudstone** formations. The dominant lithology is red-brown mudstone. In the WHS, brown sandstones constitute up to 60% of the lower formation but persist only short distances northwards, at crop, and eastwards, at subcrop; gypsum is present locally (Selwood *et al*. 1984; Edwards & Scrivener 1999)

The Exmouth Mudstone and Sandstone (255m) consists of fining-upwards sedimentary cycles in which planar- or cross-bedded sandstones, some with a basal mudstone intraclast conglomerate, rest on an erosion surface. The sandstones grade up into interbedded sandy siltstones and mudstones, the latter with mudcracks. Some of the sandstones were deposited in braided stream channels but others are aeolian dune deposits (Clemmensen *et al.* 1994). The Littleham Mudstone (275m) consists of nearly structureless, red-brown mudstones, with some thin silty and sandy beds; concretions with dark radioactive and vanadiferous cores are common in the lowest beds (Harrison 1975). These formations were deposited in an arid to semi-arid continental environment, under alternating lacustrine and desiccated mudflat conditions. Burrows, sporadic plant fragments and reworked Devonian and Carboniferous plant spores occur, but stratigraphically useful fossils are lacking. Indirect biostratigraphic evidence and magnetostratigraphy indicate a Late Permian to Early Triassic age. The position of the base of the Triassic succession may lie within this unit but is not yet determined.

The **Sherwood Sandstone Group** rests unconformably upon the Aylesbeare Mudstone Group. It comprises the **Budleigh Salterton Pebble Beds** (the 'Pebble Beds') and overlying **Otter Sandstone** formations.

The Pebble Beds (*c*.26m) consist of medium-brown conglomerates and some beds of paler brown sandstone. The former contain subrounded to rounded boulders, cobbles and pebbles, mainly of purple-grey metaquartzite, but including schorl, vein quartz, porphyry, rhyolite and sandstone, in a matrix of gravel and silty sand. In the lower part of the formation, sheets and lenses of planar cross-bedded conglomerate pass laterally into horizontally bedded conglomerate, cross-bedded sandstone and muddy sandstone; fining-upwards fluvial units with large-scale cross-bedding occur but some sandstones may be aeolian. Mudstones are scarce and are represented largely by intraclast debris. The higher beds include horizontally bedded conglomerates overlain by sandstones with large-scale cross-bedding. The formation was deposited from streams flowing north on a braidplain or antecedent 'wet' alluvial fan. Initially, stream discharge was sub-

stantial and variable, but probably permanent, in channels at least 3m deep and 16m wide. Later deposition was in channels at least 6m deep and 120m wide and may have been less permanent (Smith 1990; Smith & Edwards 1991). Reworked Ordovician and Devonian fossils (Cocks 1993) occur but the formation lacks indigenous fossils and its age is assessed, tentatively, as Olenekian (late Early Triassic), from its stratigraphic context.

At the top of the Pebble Beds, a thin, red, clayey and silty sand that is interpreted as a palaeosol (Wright *et al.* 1991), indicating a break in sedimentation and a period of pedogenesis, is overlain by a layer of ventifacts (Leonard *et al.* 1982) that marks an aeolian deflation surface. The hiatus indicated by these features is manifest as a disconformity at outcrop but farther east, at subcrop, it is emphasised by an angular unconformity between the Otter Sandstone and lower units (Butler 1998).

The lowest beds in the *c*.210m-thick Otter Sandstone are aeolian (Hounslow & McIntosh 2003). Succeeding beds include stacked fluvial sandstones, commonly with basal conglomerates resting on erosion surfaces, that form the bulk of the formation and contain bedding-parallel calcrete sheets and vertical pipe-like carbonate concretions; the latter, some >1m long, are interpreted as rhizocretions formed around the tap roots of phreatophytic plants (Purvis & Wright 1991). The highest beds consist of sandstones and interbedded mudstones, and form a transition to the overlying Sidmouth Mudstone Formation of the Mercia Mudstone Group. After an initial phase of aeolian deposition the Otter Sandstone accumulated largely from bars and sinuous dunes in frequently migrating channels of a northward-draining braided river system (Warrington & Ivimey-Cook 1992). The numerous levels of rhizocretions record repeated colonization of inactive parts of the river system by plants. Subsequently, fluvial deposition gave way gradually to deposition in a playa or an open body of water. Despite the evidence, from rhizocretions, for a prolific *in situ* flora, no spores or pollen or other stratigraphically useful plant remains have been found. The formation has, however, yielded invertebrate and vertebrate fossils (Paton 1974; Milner *et al*. 1990; Benton *et al*. 2002; Spencer & Storrs 2002). The vertebrates include fish, such as *Dipteronotus*, amphibians, and reptiles, including *Rhynchosaurus*, a herbivore, and rauisuchian archosaurs. The fauna indicates an Anisian (early Mid Triassic) age, compatible with the results of a magnetostratigraphic study (Hounslow & McIntosh 2003).

The **Mercia Mudstone Group** succeeds the Sherwood Sandstone Group conformably. In the WHS the group is constituted from four formations. In stratigraphical order these are: a thick, predominantly red-brown mudstone unit; a thin, predominantly grey and green, fossiliferous unit of fine-grained dolomitic sandstones, siltstones and mudstones; a second thick, predominantly red-brown mudstone unit, with prominent sulphate evaporites; and a second thin, predominantly grey and green siltstone and mudstone unit. The lower and upper red-brown units, the **Sidmouth Mudstone** and **Branscombe Mudstone** formations of Gallois (2001) respectively, were previously un-named in this area. The lower grey and green unit is the **Arden Sandstone Formation** of Warrington *et al.* (1980), for which the local name 'Weston Mouth Sandstone' has been used in this area (Warrington *et al.* 1980; Warrington & Scrivener 1980). Gallois (2001) suggested that this correlates with, or is younger than, the upper part of beds (his 'Dunscombe Mudstone Formation') in which halite occurs in Dorset. The upper grey and green unit is the **Blue Anchor Formation** of Warrington *et al.* (1980).

The Sidmouth Mudstone (*c*.220m) consists of red-brown, mostly structureless, dolomitic mudstones with some thin beds of siltstone and fine-grained sandstone. Secondary gypsum veins appear in the upper half and pseudomorphs after halite occur nearer the top. The formation was deposited partly under subaerial continental conditions and partly in shallow bodies of water that were connected periodically to a marine source. The thin siltstone and sandstone beds have sharp bases, small-scale cross-bedding and ripple-marked surfaces, and probably reflect brief fluvial events. The evaporites formed in shallow hypersaline lakes and their bordering sabkhas (Warrington 1974). Replenishment of brines from a marine source, coincident with syn-depositional faulting that enhanced subsidence rates locally, resulted in thick halite deposits which are present at subcrop. Miospores of Carnian (early Late Triassic) age have been recovered from the upper 65m of the formation. The lower beds have not yielded stratigraphically useful fossils but a Ladinian (late Mid Triassic) age is indicated by magnetostratigraphy and the position of the formation above the Anisian Otter Sandstone.

The Arden Sandstone (*c*.20m) includes grey and green mudstones and thin, pale grey, dolomitic, laminated siltstones and fine-grained sandstones with small-scale cross-bedding; it contrasts markedly with the predominantly red-brown mudstones of the contiguous formations. Sand-filled mudcracks, thixotropic structures and vertical burrows (*Cylindricum*) occur, and subhorizontal burrows are common. The formation accumulated in a deltaic or estuarine environment. The substantially argillaceous development in the WHS represents an interdistributary situation; elsewhere, thick sandstone bodies that formed in distributary channels are present (Warrington & Ivimey-Cook 1992). Miospores and large specimens of the crustacean *Euestheria* occur, and the formation is assigned a Carnian (early Late Triassic) age on palynological evidence (Warrington 1971).

The Branscombe Mudstone (*c*.205m) consists of predominantly red-brown, apparently largely structureless mudstone, with sporadic, very thin beds of green, very fine-grained sandstone. Gypsum is present as nodules and veins; a prominent concentration of this evaporite occurs c.75m above the base of the formation. Thin beds of green and grey mudstone, siltstone and sandy siltstone appear in the upper 35m of the formation and form a transition to the overlying Blue Anchor Formation. The Branscombe Mudstone accumulated under largely arid continental conditions, with evaporation across extensive sabkhas creating mineral-rich pore waters and hypersaline lakes from which sulphates were deposited. The formation is virtually unfossiliferous and is devoid of stratigraphically useful fossils. It is assigned a latest Carnian to Norian (early to mid Late Triassic) age on the basis of magnetostratigraphy and its position between the Arden Sandstone and the Norian? to Rhaetian Blue Anchor Formation.

The Blue Anchor Formation (*c*.25m) includes grey to green silty mudstone with some beds of red-brown mudstone and cream-coloured dolomitic siltstone in the lower part and dark grey mudstone and silty mudstone in the upper part. It records the commencement of a transgression that established marine conditions throughout much of Britain before the end of the Triassic. Supratidal sabkha conditions were gradually replaced by inter-

tidal sabkha and shallow marine environments. Palynomorph assemblages from the formation are indicative of a Norian? to Rhaetian (mid to late Late Triassic) age.

The **Penarth Group** rests unconformably upon the Blue Anchor Formation. It comprises the **Westbury** and overlying **Lilstock** formations, the latter divided into lower (**Cotham**) and upper (**Langport**) members. With the exception of the Langport Member these units are relatively poorly exposed in the WHS, largely because of landslip, and their thicknesses are based on the nearby cored Lyme Regis Borehole (Warrington & Scrivener 1980).

The Westbury Formation (*c.*9.9m) rests unconformably on the Blue Anchor Formation, on an eroded, fissured and bored surface overlain by a bone bed that contains fish remains and coprolites. The remainder of the formation consists of black shales with some thin grey limestones and sporadic sandstone laminae, and accumulated in low-energy, stagnant or weakly oxygenated marine water, with brief higher energy phases. It is fossiliferous (Swift & Martill 1999), with a fauna dominated by bivalves, such as *Rhaetavicula contorta*; diverse palynomorph assemblages comprising spores, pollen and marine organic-walled microplankton, including dinoflagellate cysts, also occur (Warrington 1997). It is Rhaetian (late Late Triassic) in age, on biostratigraphical evidence.

The Lilstock Formation is *c*.8.6m thick. The Cotham Member comprises *c*.1.9m of grey, green, yellow or brown calcareous shales and thin, cream-coloured limestones. Disturbed sediments near the middle of the member have been interpreted as a seismite (Mayall 1983), and a thin development of algal limestone ('Cotham Marble') occurs near the top in the WHS. This member is less fossiliferous than the Westbury Formation but has yielded palynomorphs, bivalves, ostracods, fish and reptilian remains and coprolites. It is commonly regarded as representing fresh- or brackish-water conditions, with periods of emergence. However, organic-walled microplankton in the palynomorph assemblages indicate a marine influence. The Langport Member comprises *c*.6.7m of pale cream-coloured limestones, some with carbonate intraclasts, and thin shale interbeds. The sediment accumulated in warm, very shallow marine water but was largely redeposited in an unconsolidated or weakly consolidated form, mainly in carbonate mudflows (Wignall 2001; Hesselbo *et al*. 2004). This member has yielded spores, pollen and marine organic-walled microplankton, including dinoflagellate cysts (Warrington 1997), conodonts (Swift 1995), and macrofossils, including marine indicators such as corals and echinoderms (Swift & Martill 1999). Its top is an erosion surface penetrated by *Diplocraterion* burrows. The Lilstock Formation is Rhaetian (late Late Triassic) in age on biostratigraphic evidence.

In the WHS the base of the Jurassic is placed at the appearance of psiloceratid ammonites, some 2.5m above the base of the **Lias Group** (Page 2002). The youngest Triassic rocks exposed in the WHS are, therefore, the lowest beds of this group which are seen as far east as the east side of Pinhay Bay, only *c.*1.5km west of Lyme Regis harbour.

The concealed succession

The succession in the concealed part of the 'iceberg' is known from borehole records, augmented by the interpretation of seismic records; some parts, such as the Otter Sandstone in the Wytch Farm oilfield, are locally better known than others.

Coarse clastic units analogous to the Exeter Group occur locally between Variscan Basement rocks and the Aylesbeare Mudstone Group in west Dorset. These occurrences are not in proven continuity with the outcrop of the group and their age is constrained only by their stratigraphic position.

At subcrop the Aylesbeare Mudstone Group occurs largely to the south of faults that mark the northern margin of the Winterborne Kingston Trough (Bristow *et al*. 1995; Butler 1998). It is *c*.530m thick in the WHS but >800m farther east in Devon; it thins to less than 200m over the South Dorset High, from where it thickens south-eastwards to >1000m in the Swanage area and >1400m offshore in the Portland-South Wight Trough (Butler 1998). The Wytch Farm Breccias, in the Wytch Farm area, are regarded as a basal unit of the Aylesbeare Mudstone Group (Butler 1998), rather than a representative of the older Exeter Group.

The Sherwood Sandstone Group is more widely developed at subcrop than the Aylesbeare Mudstone Group and extends onto the Cranborne-Fordingbridge High (Bristow *et al*. 1995; Butler 1998). However, thicknesses are less variable, with *c*.235m in the WHS and a maximum of <400m in west Dorset (Butler 1998). In south-east Devon and much of west Dorset the Otter Sandstone rests on the Pebble Beds, but farther east the latter are absent and it rests on the Aylesbeare Mudstone Group or older rocks (Holloway *et al.* 1989). The absence of the Pebble Beds in east Dorset has been attributed to non-deposition (Smith & Edwards 1991) but is now understood to result from erosion that followed Early Triassic Earth movements, prior to deposition of the Otter Sandstone. In west Dorset, an un-named argillaceous unit locally separates the Pebble Beds and what is interpreted, from seismic sections, as an angular unconformity overlain by the Otter Sandstone (Butler 1998). Similar situations occur in correlative sequences elsewhere in England, and an unconformity at this level is a regional feature comparable with the Hardegsen Discordance in Lower Triassic successions in Germany and the North Sea.

The Pebble Beds are up to 46m thick in west Dorset, and the succeeding, entirely concealed, argillaceous unit is up to 65m thick. The Otter Sandstone is locally thicker in east Devon and west Dorset than in the WHS, with >300m present north-west of Weymouth; elsewhere in Dorset it is typically thinner than at outcrop. In the Wytch Farm oilfield, where the formation is a reservoir unit, it is *c*.150m thick (McKie *et al.* 1998).

The thickness of the Mercia Mudstone Group varies considerably at subcrop, in contrast with the underlying Sherwood Sandstone Group, and is greatest where halite is present, in western and south-central Dorset. Here the group is mostly 600-700m thick but reaches nearly 1000m north of Weymouth; it is 300-500m thick where halite is absent; for example, at Wytch Farm. The halite, which is not seen at outcrop, occurs beneath some 1200 sq. km. of western, central and southern Dorset, to the south of the northern margin of the Winterborne Kingston Trough (Butler 1998). Determination of the original thickness of the group, and the degree to which this was influenced by syndepositional faulting, is complicated by the presence of the halite which forms a décollement zone in which younger listric faults sole-out; subsequent halokinesis has caused considerable variation in the thickness of the group in the hanging walls of such faults.

Gallois (2003) considered the halite to be largely confined to beds (his 'Dunscombe Mudstone Formation') that he regarded (*idem*

2001) as older than, or only partly correlative with, the Arden Sandstone. The halite is here interpreted as within the Sidmouth Mudstone which is locally >600m thick where halite is present in south Dorset. The halite-bearing interval is up to 488m thick locally, but is very variable. Individual units of relatively pure halite are mostly 20 to 40m thick but locally >60m, and are interbedded with mudstone (Harvey & Stewart 1998; Highley *et al*. 2001).

The Branscombe Mudstone is locally >300m thick but is generally less variable in thickness than the underlying, halite-bearing succession and its equivalents. A prominent geophysical marker at the base of Unit D of Lott *et al.* (1982) is widely recognised in borehole records and is now known to correspond with the concentration of sulphate evaporites c.75m above the base of the formation in the WHS, rather than the underlying Arden Sandstone.

The Blue Anchor Formation is slightly thicker at subcrop than in the WHS; it is typically <40m thick but reaches >70m north of Weymouth.

The Penarth Group is *c.*18.5m thick in the WHS but is generally thicker at subcrop, with a maximum of 42m present north of Weymouth. The Westbury Formation locally exceeds 12m at subcrop. The Lilstock Formation is commonly >12m, and locally >16m, thick at subcrop.

Summary

The 'red rocks of the west' record palaeogeographic changes that occurred in the region of the WHS through some 95 million years, following the end of the Variscan orogeny. The Permian and Early Triassic successions, though incomplete, record the change from post-orogenic, juvenile landscapes of the Early Permian, with volcanics and eastward transport on alluvial fans, to the dune-covered deserts and extensive playas of the Late Permian/Early Triassic, and a northward-draining Early Triassic river system. Following regional Earth movements, a relatively complete Mid and Late Triassic succession records the change from a Mid Triassic northward-draining river system to playas and hypersaline lakes and, finally, to a passage from supra- and intertidal sabkhas to marine environments, such as the warm, shallow, carbonate-rich sea in which the Langport Member was deposited just before the start of the Jurassic Period.

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Book review

The Oceans and Climate 2nd Edition by Grant R Bigg, 2003, Cambridge University Press, 273pp, £24.95 (paperback), £60.00 (hardback), ISBN 0521016347(PB), 0521815703(HB)

The book, as the title suggests, investigates the complex relationship between the oceans and global climate. Divided into seven chapters, the major topics are:

- The climate system.

- The physical, chemical and biogeochemical interaction of the atmosphere and ocean.

- Large-scale air-sea interaction.

- The ocean and natural climatic variability.

- The ocean and climatic change.

Four appendices:

- Physical constants and the electromagnetic spectrum.

- The periodic table and electron orbital configuration.

- Stability, potential temperature and density.

- Rossby waves in the atmosphere and ocean.

A comprehensive glossary and bibliography complete the book.

Each chapter is subdivided into relevant topics and the text throughout is reinforced by a large number of maps, graphs, tables and schematic illustrations. The complicated interaction of physics, biology, chemistry and geology, past and present, to produce the conditions we experience today is gradually developed.

Chemical and mathematical formulae are abundant, requiring a high level of understanding in each discipline to fully appreciate the information contained in the book. Nonetheless, simply reading the text and cross-referencing the diagrams and tables provides a wealth of information to those approaching the subject for the first time.

There are, however, a couple of criticisms I have to make. The first is the lack of colour. All the illustrations are black and white. I appreciate that a considerable amount of information can be conveyed in a simple monochrome diagram, but there were occasions when my eyes could not differentiate the seventeen different shades of black, white and grey required to interpret some of the diagrams. The second criticism concerns the mathematics. There is no attempt to construct equations. In the midst of the text the equation suddenly appears with the information that it describes a certain condition but the question why does not seem to be answered.

Putting the criticisms to one side I found the book very interesting. Never having had more than a passing interest in the subject I found the book answered a number of questions I had not realised I wanted to ask. I have now added Oceanography to my list of courses to do.

Mike Steele, BSc, Continuing student

The Kimmeridge Clay: the most intensively studied formation in Britain

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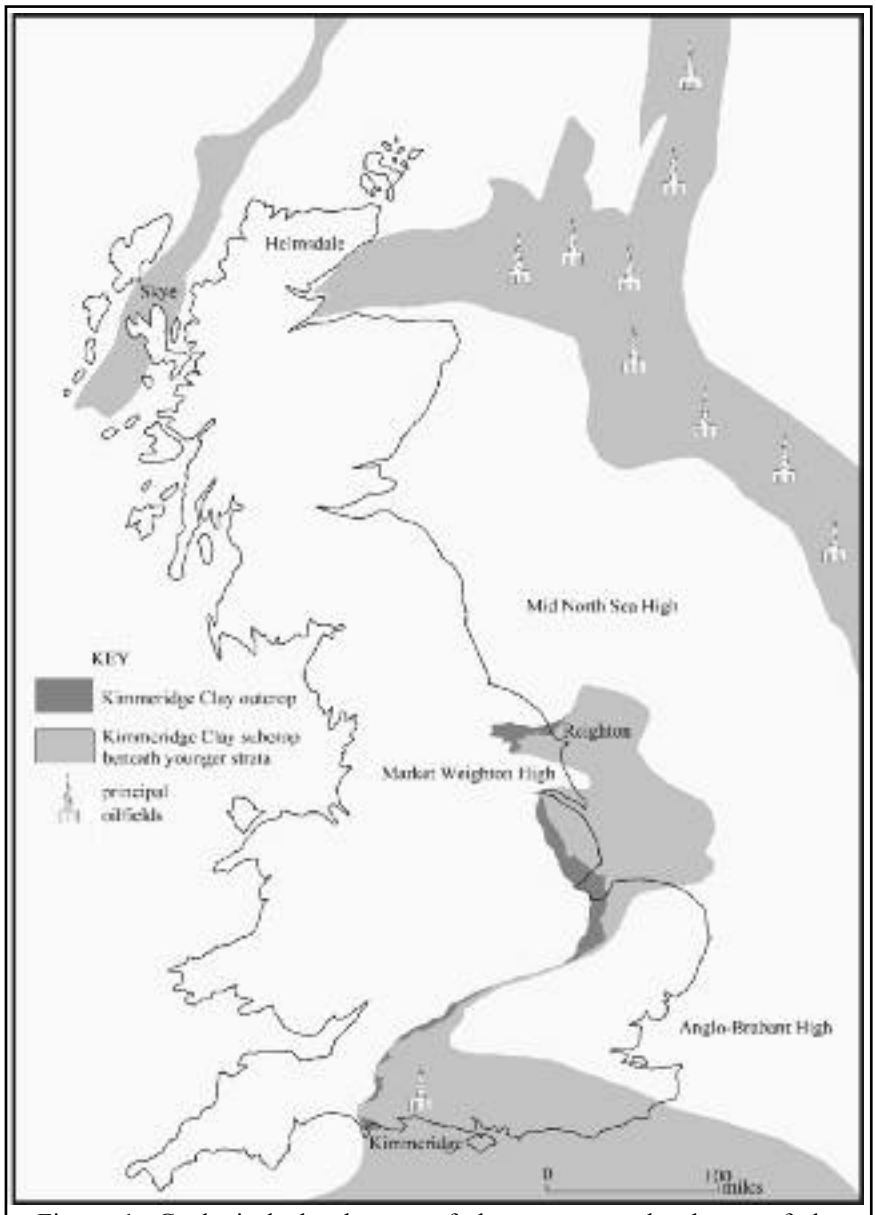

Figure 1. Geological sketch map of the outcrop and subcrop of the Kimmeridge Clay.

Introduction

The Jurassic rocks of the World Heritage coast crop out over a distance of about 60 miles between Lyme Regis and Swanage, and represent an unbroken 60 million years of Earth history. Within this succession marine mudstones, principally the Lias Group and the Oxford Clay and Kimmeridge Clay formations, represent about 60% of the time interval. Of these, the Kimmeridge Clay has been the most extensively studied with the result that much is known about its lithostratigraphy, biostratigraphy and geochemistry. Many of the lithological and faunal associations found in the Kimmeridge Clay can be closely matched with those in the Lias and Oxford Clay. All three were deposited in relatively shallow (50m to 200m deep), fully marine environments on continental shelves, and many of the conclusions reached about the depositional history of the Kimmeridge Clay can be equally well applied to the other formations.

The Kimmeridge Clay outcrop runs almost continuously from the Devon coast to the Yorkshire coast, and the formation has an extensive subcrop beneath younger rocks in eastern England and the North Sea (Figure 1). At outcrop the mudstones weather rapidly to clay with the result that there is no natural inland exposure, and at any one time there are rarely more than five man-made sections. The only good exposures are in the cliffs at and adjacent to Kimmeridge and Ringstead bays, and these form the type sections for the Kimmeridge Clay Formation and the Kimmeridgian Stage (Arkell 1947; Cox & Gallois 1981).

Lithostratigraphy

At first sight, the Kimmeridge Clay looks monotonously uniform with almost no lithological variation and little colour contrast other than shades of grey. There are, however, variations in the cliff profiles in which more resistant horizons are interbedded with more friable lithologies. These correspond principally to variations in the clay, calcium carbonate and organic contents of the mudstones. When examined in detail, it can be seen that these variations are rhythmic at scales ranging from millimetres to tens of metres in thickness. A few thin muddy limestones (cementstones), eight or nine horizons in the 550m-thick Dorset succession, form prominent marker beds in the cliffs.

Almost all the lithologies in the Kimmeridge Clay can be expressed in terms of their siliciclastic, calcium carbonate and organic contents (Figure 2). The organic contents are mostly kerogens, complex organic polymers with very high molecular weights that formed within the sediment by the action of chemical and bacterial degradation on recently buried decaying organic matter. Kerogens impart a brown colour to the mudstones, and when present in sufficiently high concentrations give rise to oil shales. Increases in calcium carbonate content cause the mudstones to become paler grey until they pass into chalk-like sediments.

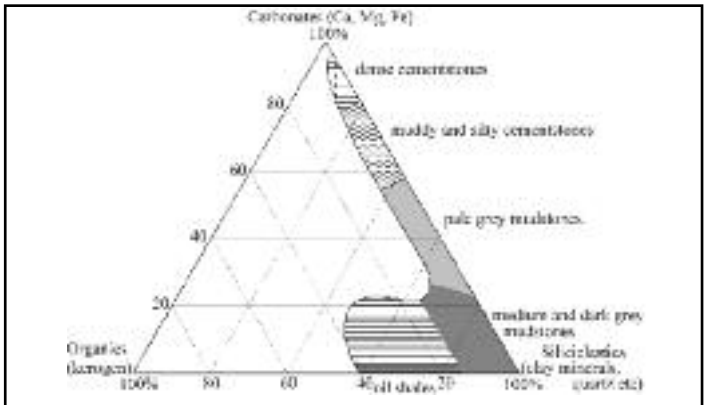

Figure 2. Diagrammatic representation of the bulk chemistry of the more common Kimmeridge Clay lithologies.

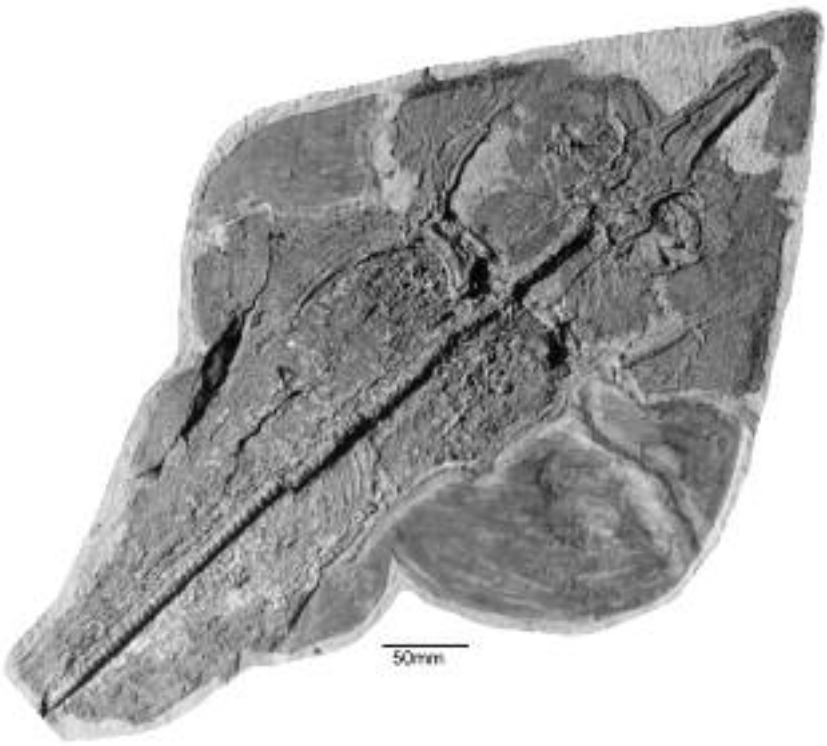

Figure 3. Almost complete specimen of a ray (Rhinobatidae): Etches Collection No. K1281.

These components can be divided into three genetic groups: clastic, biogenic and chemogenic. The clastic components consist of clay minerals, detrital quartz and re-worked biogenic and chemogenic materials such as shell and plant debris, and phosphatic pebbles. The biogenic components consist of calcareous fossils, principally ammonites, bivalves and foraminifera with lesser numbers of gastropods, brachiopods, serpulids, crinoids, ostracods and coccoliths; phosphatised fossils, mostly vertebrate debris such as fish scales, vertebrae and faecal pellets; and kerogens derived from dinoflagellates, acritarchs and plant debris including pollens. The chemogenic components consist principally of diagenetically formed calcium and magnesium carbonate concretions and cements, pyrite and phosphate.

Using the parameters of colour, texture, grain size and shell content, a wide range of lithologies can be readily recognised in borehole cores and hand specimens. These can be closely correlated with the mineralogy and chemistry of the mudstones. The lithological logs can be calibrated against geophysical logs made in cored boreholes, and then used to make correlations over long distances in uncored boreholes in areas where the formation is not exposed (Penn *et al*. 1986). In the more extreme examples, individual beds less than 0.3m thick have been traced over distances of more than 200km. At such horizons, the depositional environments must have been closely similar over areas in excess of 40,000km^2 .

Biostratigraphy and Chronostratigraphy

The Kimmeridge Clay is richly fossiliferous, despite the statement in British Mesozoic Fossils (Anon, 1983, p. 5) that it is not particularly attractive to the collector, and has yielded as great a range of fossils as almost any other Mesozoic formation in Europe. In addition to the profuse invertebrate fauna described above, the exposures in Kimmeridge Bay have yielded a variety of marine reptiles and fish (Figure 3), and several exotic finds (Etches & Clarke 1999). One of these last is a dragonfly wing (Figure 4) that was preserved at least 160km from the nearest land. As elsewhere along the World Heritage coast, geology is deeply indebted to the small number of highly skilled 'amateur' collectors, starting with Mary Anning and her contemporaries, who have provided almost all the material on display in museums.

The vertebrate and exotic fossils are of enormous interest when it comes to the reconstruction of Kimmeridgian depositional environments. They help us to understand who lived where within the water column and seabed sediment, how they lived, and who probably ate whom. However, they provide little stratigraphical information. For that we have the ammonites, the stratigraphically most important fossils in the Jurassic, where they are used to make regional correlations that are an order of magnitude more accurate than is possible using any other fossil group.

Most of the ammonites in the Kimmeridge Clay are crushed, but their distinctive ornamentation is commonly preserved and they occur in sufficiently large numbers throughout the formation to form the basis for a detailed zonation (Callomon & Cope 1995). In the early Kimmeridgian, Britain lay in the southern part of a cool Boreal Sea with a warmer Tethyan Ocean several hundred miles to the south. The ammonite assemblages reflect this with dominantly Boreal species, but also a few wide-ranging forms that can be traced into the Tethyan Province. Earth movements in the later Kimmeridgian produced new land areas and caused what had been an extensive continental shelf to break up into separate marine basins. These became progressively more isolated from one another with time, and each developed its own, separately evolving fauna. As a result, even within the Boreal Province there are different zonal schemes for northern Boreal, sub-Boreal, and Franco-German areas, and long-distance correlations become progressively more difficult to make with time.

Fortunately, the Kimmeridge Clay contains additional faunal elements that form stratigraphically specific marker beds at several levels. These include the small bivalve Nicaniella (formerly Astarte) which has a long stratigraphical range but which occurs by the billion in one bed about 1m thick (the Supracorallina Bed

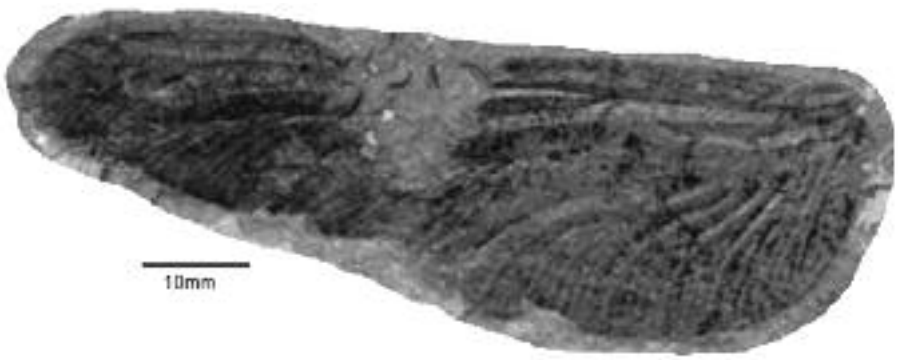

Figure 4. Dragonfly wing: Etches Collection No.K619. The first recorded insect remains from the Kimmeridge Clay.

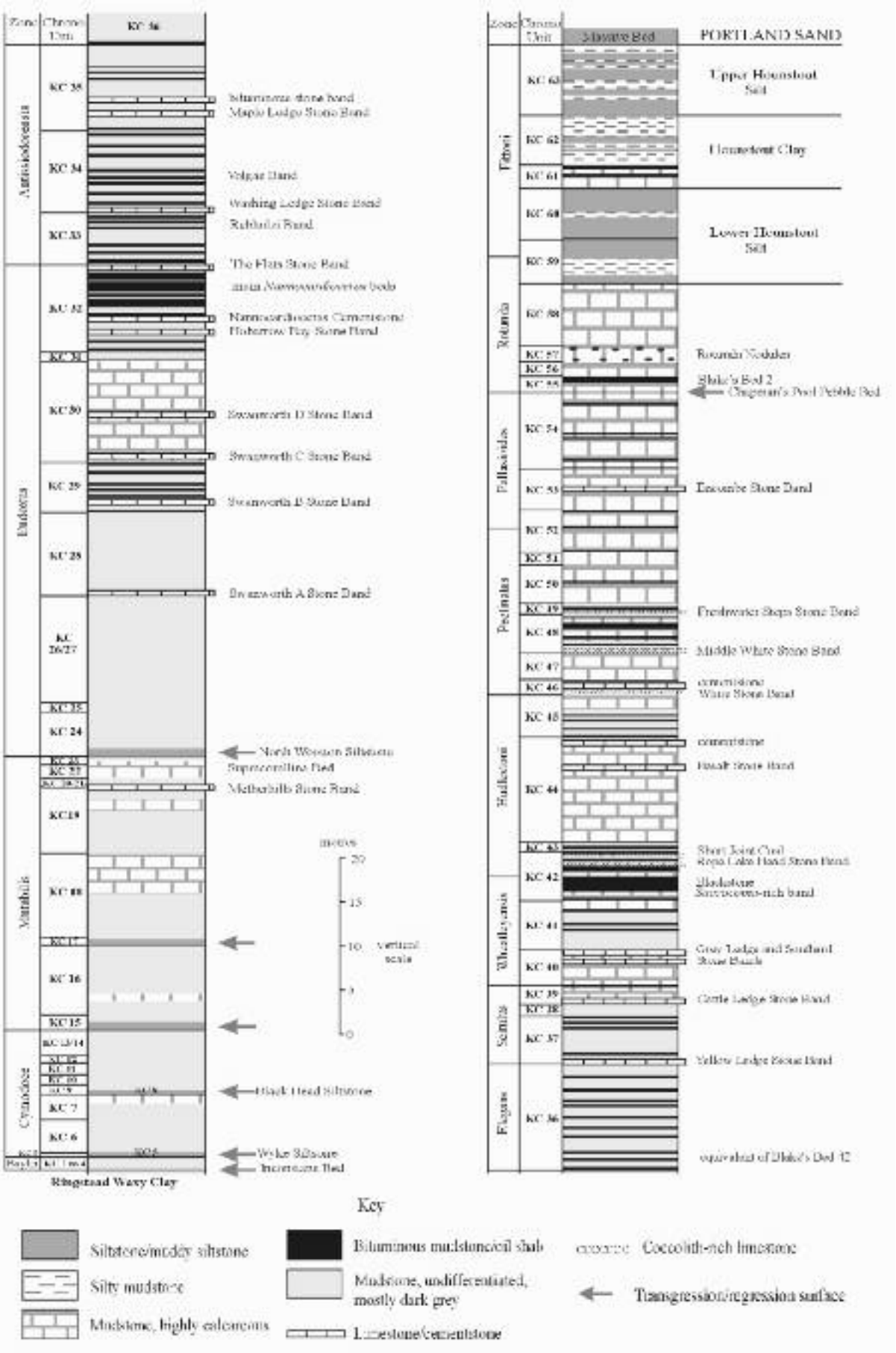

Figure 5. Summary of the Lower Kimmeridge Clay (KC1 to KC35) and Upper Kimmeridge Clay (KC 36 to KC63) successions of the Dorset coast (after Gallois 2000).

of Arkell, 1933) that can be traced throughout the outcrop from the Dorset to Yorkshire coasts. This 'flood occurrence' can be matched by that of the tiny free-swimming crinoid Saccocoma whose pyritised remains are restricted to four horizons, each only a few millimetres or centimetres thick, that can also be traced throughout the outcrop.

When the lithostratigraphy of the Kimmeridge Clay is combined with the biostratigraphy and the geophysical log signatures it enables the formation to be divided into 63 chronostratigraphical units (Figure 5) that can be recognised throughout the onshore outcrop and subcrop (Gallois, 2000). Current estimates based on radiometric dating suggest that the Kimmeridge Clay was deposited over a period of about seven million years, which suggests that the average time span represented by the chronostratigraphical units is a little more than 100,000 years. This is about five times more accurate than the ammonite zonation. The availability of a chronostratigraphy has made it possible to develop a sequence stratigraphy (Taylor *et al*. 2000) that should enable international correlations to be made that are complementary to but independent of the biostratigraphical correlations.

Kimmeridge Clay as an oil source rock

Although the KC is worthy of study because it has much to tell us about Earth history in this part of the Jurassic, most of the research into its stratigraphy, sedimentology and geochemistry has been prompted by its economic importance. In the northern North Sea, the primary energy resource is oil derived mostly from the geothermal breakdown of the kerogens in the deeply buried Kimmeridge Clay. They are also the principal source of the oil in Britain's largest onshore oilfield at Wytch Farm, Dorset (Figure 1).

The most famous source rock at outcrop in the cliffs at Kimmeridge Bay is the 60cm-thick Blackstone. This has an organic carbon content of more than 50% and yields 60 gallons of oil per ton of rock when retorted. The high kerogen content imparts a translucent, dark mahogany colour to the rock, and enables it to be carved and polished. It was used in the Iron Age and by the Romans to make ornamental vases and bowls, and probably also as a fuel. From medieval times onwards this last was its principal use under the name Kimmeridge Coal. It burns with a sooty, foul smelling flame on account of its high sulphur content, and leaves behind large quantities of ash impregnated with organic carcinogens. The 17th century entrepreneur Sir William Clavel used the Blackstone as the heat source to make alum from shale and glass from sand, and to extract salt from seawater. It was also used domestically until the 1930s. Accounts of rural Dorset by Victorian gentlemen travellers describe evil smelling peasants crouching around smoky fires in their sooty hovels.

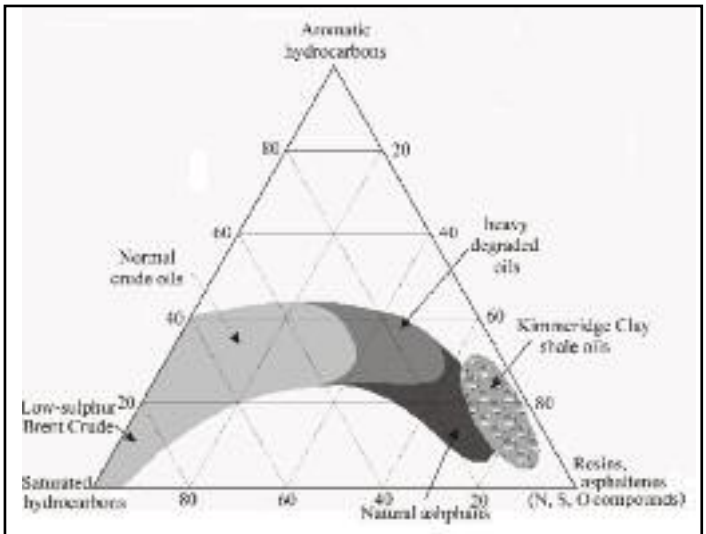

Figure 6. Relationship of Kimmeridgian shale oils to naturally occcuring 'hydrocarbon' deposits.

The organic content of the Kimmeridgian oil shales can be divided into two parts. Bitumens can be extracted with organic solvents and make up 5% to 8% of the total organic content. They consist of complex compounds derived from the proteins, carbohydrates and lipids ('fats') in the fossil biomass, and can provide geochemical signatures that link them to living organisms. Almost all the remainder of the organic content is in the form of kerogens, insoluble, high-molecular-weight polymers that have to be heated in the laboratory to 400-500°C before they will yield oil. In nature, the same result can be achieved at temperatures as low as 50°C, but over a period of millions of years (Tissot & Welte 1978).

Naturally occurring organic compounds, popularly referred to as 'hydrocarbons', consist of complex mixtures of saturated (e.g. methane) and unsaturated (e.g. benzene) hydrocarbons and 'resins' (asphaltenes, organic nitrogen sulphur, oxygen (NSO) compounds). Shale oils obtained by retorting oil shales from the Kimmeridge Clay are rich in these last (Figure 6), and would have to be distilled before they had any commercial value. The high sulphur content of up to 8% would be particularly expensive to remove because it generates corrosive sulphuric acid. In contrast, 'sweet' crude oil such as that from the Brent Field in the North Sea, are rich in hydrocarbons and have only 0.5% sulphur, their refinement having been performed naturally over a period of 50 million years.

Geochemical analyses of the bitumens, particularly of the saturated hydrocarbon fractions, have shown that most of the organic matter preserved in the Kimmeridge Clay was derived from phytoplankton, mostly microscopic marine algae. The algae themselves are rarely preserved except where they secrete a calcareous (e.g. coccolithophores) or chitinous (e.g. Tasmanites) protective layer. At a few horizons pure white limestones are interlaminated with oil shales, and these provide a clue to the origin of the organic matter. Under the electron microscope the limestones can be seen to be composed entirely of coccoliths with no interstitial sediment. At the present time, coccolithophores form 'algal blooms' during short periods of the year when they occur in concentrations of billions per litre of seawater, enough to colour the sea milky white. Pictures taken of the floor of the north Atlantic shortly after one of these blooms showed the seabed to be covered with a brown, gelatinous mass, the result of cyanobacterial degradation of the rotting remains of a bloom. Such material, if protected from oxidation by a covering of sediment or a layer of anaerobic water, contains all the ingredients to produce the organic content of the Kimmeridgian oil shales.

Much of the geochemical research on the Kimmeridge Clay has been driven by the desire to determine the optimal depositional environments for the preservation of high organic contents, and where they occur. In the right tectonic and stratigraphical setting, the best source rocks should give rise to the richest oil deposits. However, although the organic chemistry of the oil shales has become known in more and more detail, it has added little to the long-running

Figure 7. Alternations of organic-rich (weathered as hard ribs) and carbonate-rich mudstones at Kimmeridge Bay.

debate about the relative importance of productivity and preservation. Organic-rich rocks such as those in the Kimmeridge Clay were obviously derived from marine environments that were teeming with life, but was the organic productivity of the Kimmeridgian sea markedly different from that of present-day seas?

The answer to that question lies in the ratio of the organic production to the organic preservation. Even the richest oil shales preserve only a fraction of the potentially available organic material that is generated in fertile sub-tropical seas such as that of the Kimmeridgian. The ultimate fate of the biomass is almost entirely determined by the extent to which it is degraded by oxidation prior to being trapped in the rock. It depends, therefore, on the redox potential of the water column and near-seabed environments, and the biochemical interactions that take place as the organic material passes through these layers. The amount of material from the same biomass source that survives in the rock (usually expressed as weight percentage Total Organic Carbon-TOC wt%) can vary by several orders of magnitude as a result of these processes. The greater the degree of oxygenation, the higher the primary organic productivity that has to be assumed to explain the TOC percentages observed in the rock.

There is much that we do not know about the food chains in the water column and the top part of the sediment into which the organic matter is incorporated, in particular the roles of viruses and bacteria. Even the most sophisticated attempts to estimate the primary productivity of the Kimmeridgian sea still have to operate within what the sedimentology tells us are the most likely boundary parameters. Namely, that in Dorset the lower water column/seabed conditions were in the range sub-oxic (no organic-oxygenating organisms) to dysoxic (Tyson 2004).

Cyclostratigraphy

The most striking feature of the Kimmeridge Clay at Kimmeridge Bay is its cyclicity. Oil shales alternate with calcareous mudstones to weather out as harder and softer ribs in couplets about one metre thick (Figure 7). These alternations have long been regarded as the product of climate changes related to Milankovitch cycles, those at Kimmeridge Bay being thought to be linked to changes in the obliquity of the Earth's axis (House, 1985). Much of the remainder of the Kimmeridge Clay does not appear to the naked eye to be cyclic. One can see small- and large-scale variations from more to less organic-rich and more to less calcareous in the cliff exposures, but these do not appear to form rhythmic patterns.

However, analyses of the distribution of TOC and properties such as radioactivity that are not visible to the naked eye, have shown that the whole of the Kimmeridge Clay succession is cyclic (Weedon *et al.* 2004) (Figure 8). The recognition that the formation contains Milankovitch-related cycles is of practical value for several reasons. First, by counting the number of cycles of known duration (precessional cycles of 19ka and 23ka; obliquity cycles of 38ka etc) it is possible to obtain a more accurate estimate of the time taken to deposit the formation than that currently available from radiometric dating. This can then be used in combination with the geochemical data to estimate the average annual rate of organic productivity of the Kimmeridgian sea. Surprisingly, given the organic-rich nature of much of the formation, it indicates an average productivity less than that of modern continental shelves (Weedon *et al*. 2004).

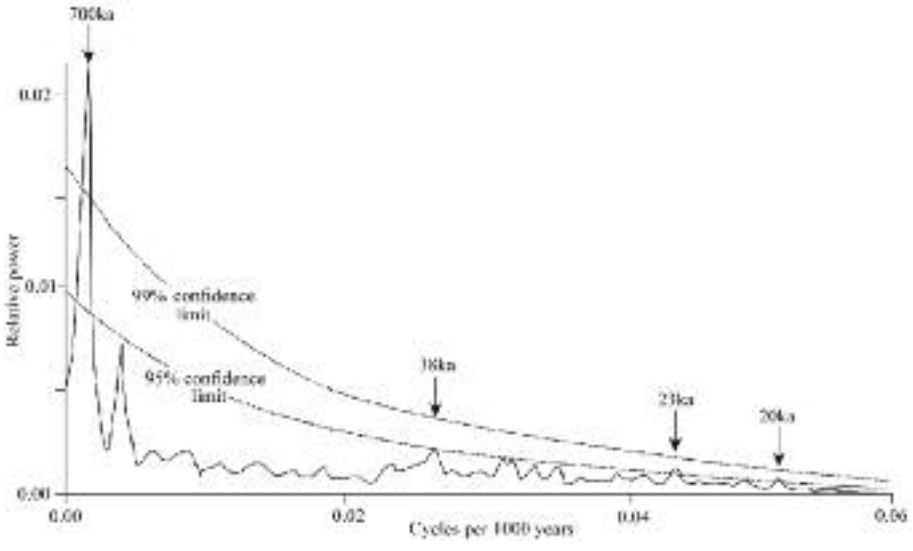

Figure 8. Statistical analysis of organic-carbon contents in Kimmeridge Clay cores from the Swanworth No.1 Borehole, Dorset revealing Milankovitch cycles at various time scales (after Weedon *et al*. 2004).

Second, the basis for computer modelling future climate change in Britain is based on detailed climatic records that extend back only about 150 years. Whilst they may be adequate for detecting recent changes, the only place where changes at the Milankovitch scale can be studied is in the geological column. The Kimmeridge Clay, with its unusually complete, marine sedimentary record is one of the best places in the stratigraphical column to do this.

Conclusions

Although the Kimmeridge Clay can be said to be the most intensively studied formation in Britain, there is still much that we do not

know about the depositional environments and subsequent diagenesis that produced the present-day rock. As with all branches of science, the more we know the more we realise we don't know.

The chronostratigraphy and sequence-stratigraphy of the English onshore outcrop and subcrop of the formation is well established, but the correlation with European sections and with the deep-water successions of the UK continental shelf is poorly known at many stratigraphical levels. The biostratigraphy of the ammonites has been studied, but that of much of the rest of the fauna has not. In particular, the vertebrate fauna, which in the Jurassic is matched in diversity and quality of preservation only by that from the Solnhofen Limestone, has barely been studied despite the availability of extensive collections.

Recent models of the depositional environments of the Kimmeridge Clay of the 550m-thick Dorset succession have assumed an outer-shelf water depth of 150 to 200m. Elsewhere in England, where the correlative deposits are locally less than 100m thick (Penn *et al.* 1986), the same lithological and faunal associations and sedimentology suggest deposition in similar outer-shelf environments. In order to explain the thickness variations whilst retaining the chronostratigraphy, one has to postulate complex interactions between eustatic changes in sea-level, climate changes, sedimentation rates and tectonically induced subsidence rates. More parameters than we can cope with at present.

In short, the Kimmeridge Clay is a very interesting and much studied formation, but one about which we still have much to learn.

References

The references listed below have been selected to illustrate particular features of the Kimmeridge Clay. A detailed, comprehensive account of the formation including an extensive list of references is given on Dr Ian West's web site at www.soton.ac.uk/~imw/kim.htm

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Book review

The Sedimentary Record of Sea-Level Change by Angela L. Coe (ed); contributory authors: Angela L. Coe; Dan W.J. Bosence; Kevin D. Church; Stephen S. Flint; John A. Howell, R. Chris L. Wilson, 2003, The Press Syndicate of the University of Cambridge, 287pp, paperback £28, ISBN 0521538424, hardback: £75, ISBN 0521831113.

This book forms part of the Open University undergraduate course S369 "The Geological Record of Environmental Change". It has been a joint production by the Open University with Cambridge University designed to be used on advanced undergraduate and graduate courses. In association with the book is a website hosting sample pages, illustrations and worked exercises.

The book is beautifully presented with all photographs, diagrams and illustrations in colour. There are four parts to the book 1) Introduction, 2) Sequence stratigraphy and sea-level change, 3) Siliciclastic case study : The Book Cliffs and 4) Carbonates.

Part 1: The introduction examines the importance of sedimentary rocks and their usefulness for determining sea-level change, how geological time is determined, introduces sea-level change and examines possible evidence for Noah's flood.

Part 2: Takes one through the theory of sequence stratigraphy and the mechanisms for sea-level change finishing with a case study from the Gulf of Mexico.

Part 3: Concerns itself with a detailed case study of the siliciclastic succession from the Book Cliffs, Utah, USA. A 300km long by 300m high cliff showing well exposed fluvial to open marine deposits.

Part 4: Examines how carbonate sediments respond to sea-level change and how modelling can predict different stratigraphical geometries and successions using case studies from Mallorca and North East Spain.

The associated website hosts various exercises plus model answers, particular figures, additional figures, sample pages, links to other websites, errata (none for this particular book) and figure captions. Useful if using the book as suggested "as a teaching text for independent study".

I have enjoyed reading the book. This is probably why it has taken so long to produce the review. I can thoroughly recommend "The Sedimentary Record of Sea-Level Change" as a memory jogger as well as a teaching aid. If the rest of the books in S369 are as good as this one it should prove a popular course.

The cost of the book will not exclude it from my library shelf.

Mike Anderson, BA Hons(Open), Msc(Science)

A View of 'Purbeck Park' – the Purbeck Limestone Group of Dorset

Paul Ensom, Department of Palaeontology, The Natural History Museum, London.

The Purbeck Limestone Group of Dorset is a truly remarkable formation, straddling the Jurassic – Cretaceous boundary which has been variously placed within the sequence. The strata are sedimentologically varied with limestones and subordinate calcareous sands and sandy limestones, shales and clays, and evaporites especially in the lower part of the formation. The sediments represent a range of environments originating in the hypersaline, brackish, freshwater and occasionally 'marine' conditions which existed at different times. In addition to these aquatic environments, there were times when the sediments were exposed to subaerial processes. The current exposure of the Purbeck Limestone Group is the basis of 'Purbeck Park', an area in the eastern portion of the 185Ma Timewalk which is the Jurassic Coast, or if you prefer, The Dorset and East Devon World Heritage Site. These strata were deposited around 140Ma ago, at a time when the ruling terrestrial vertebrates were dinosaurs, a little over half way through their 180 million year domination of the terrestrial sphere. Dinosaur tracks are often abundant and provide good evidence of a contemporaneous dinosaur population, compensating to some extent for the rarity of their actual remains. These varied environments supported an equally varied flora and fauna. A rich microflora has been recorded, the remains of macro-plants are well known, and invertebrates are at times so abundant that they become important components of the rocks. Fish remains are frequently encountered, and alongside the terrestrial dinosaurs we have evidence of diminutive amphibians, a wealth of other reptiles and the well established, but still relatively primitive, mammals. Reptile eggshell is being found at an increasing number of horizons. The depositional regime of the Purbeck Limestone Group provided the perfect conditions for the preservation of the abundant life and the traces it left. The considerable scientific importance of the Purbeck Limestone Group, exposed on the Dorset coast, is one of the many reasons why the Dorset Coast along with a section of that in East Devon became the UK's first geological World Heritage List site. This talk will briefly review aspects of the Purbeck Limestone Group drawing on the work of the speaker and the many others who have worked on, and written about, these extraordinary strata.

Introduction

The Purbeck strata have been a focus of interest for geologists and specifically palaeontologists since the mid 19th century (Austen 1852, Owen 1854, 1855, 1871, 1874-89, 1879, Woodward 1916-1919, Arkell 1941, and many authors in Milner & Batten 2002). Before that the Purbeck Beds' beautiful limestones, along with the massive alabaster in the Soft Cockle Member, had been quarried and used in buildings and monuments across much of England (Austen 1852, Hutchins 1861, Drury 1949). Doubtless, during the quarrying operations fossils were found, but to a large extent we can only speculate on what the quarrymen and those that owned the land, if interested in the first place, made of these petrified remains of the denizens of the long-past Purbeck world which I am about to describe.

Before doing so, I should explain how I come to be so fascinated by these strata. I was very fortunate to be appointed as Assistant Curator at the Dorset County Musum in 1978. This museum, owned and run by the Dorset Natural History & Archaeological Society, was blessed with a small (*c.*10,000 specimens) but very fine collection of fossils, representing the 200 million year sequence of sediments present in the County. Not least amongst these was a collection of fossils from the 'Purbeck Beds', amongst which vertebrate remains were well represented. However, this collection was but a shadow of that described by Arthur Smith Woodward in 1896. He told the then Curator, 'that outside that Museum [i.e. the British Museum (Natural History)], no collection of Purbeck reptiles and fishes in the country is worthy to be named with ours.' Through this collection and some remarkable discoveries across the Isle of Purbeck and adjacent areas over the last 25 years, and with the involvement and support of colleagues and friends at the Dorset County Museum, colleagues at the Yorkshire Musem, at the NHM and in other institutions, I have had the enormous pleasure of playing some part in helping to unravel the history of these fascinating strata. Last but not least I acknowledge my parents and family who have encouraged and supported me.

Through the work of Perce Allen, David Batten, Jane Francis, Ross Garden, John Underhill, Ian West and many others, we have been given increasingly vivid glimpses of this late-Jurassic/early-Cretaceous landscape. There were shallow-water lakes and lagoons fringed by sparse conifers, mudflats and shell-banks which from time to time were exposed and baked in the sun, and sometimes populated by egg-laying reptiles including dinosaurs. The latter frequently left their tracks, and mammals lived close by, if not actually scurrying around their feet. Pterosaurs wheeled in the warm air occasionally landing to feed.

But before looking at these environments in more detail, let us start by defining 'Purbeck Park'. In writing this article I have included the area in which the Purbeck strata are exposed in Dorset, namely from Portland north to Portesham in the west, eastwards to Durlston Bay.

We may now consider where Dorset was at this time, what the landscape looked like and why. If we as 'geo-time-tourists' were to set off from Canford School now, where would we have to go to find 'Purbeck Park', and what would we see when we got there?

Where was the Isle of Purbeck then?

To start with we would have to travel back around 140Ma, and a fair way south of where we are now! A location at around 40°N of the equator, somewhere in the region of the Mediterranean or North Africa today is accepted. What can be regarded in general terms as the 'NW European Craton' upon which the UK sits had been flooded during the early Jurassic transgression, and Dorset had remained more or less submerged as a marine environment throughout the Jurassic period. Now this shelf area, while not totally immune to tectonic influences over the previous 60Ma, was becoming the subject of increasingly significant tectonic stress caused by extensional forces across the incipient rift systems in the North Atlantic, North Sea and south-west Approaches. Amongst other things, these forces were responsible for the reactivation of deeply buried fault systems under Dorset and much of

southern England. The surface traces of these deep structures can be seen emerging westwards from beneath the unconformable Mesozoic and uppermost Palaeozoic cover in eastern Devon. These structures have been further plumbed across Dorset by the deep boreholes put down by an oil industry which recognised the potential for significant oil and or gas deposits beneath Dorset's stunningly beautiful landscapes. These stresses resulted in a shallowing of the sea, and the onset of a more restricted marine environment as deduced from the sediments of the Portland Limestone Group. While the marine sediments of the Portland Limestone Group were being deposited across southern Dorset (their northerly extent in the county is not known as they are not present below the Mid-Cretaceous unconformity of west and north Dorset due to either erosion, non-deposition or a combination of both), to the north of Dorset, sediments deposited in the Swindon area were of what we would consider to be a Purbeck facies. We may deduce from this that there is a degree of diachroneity within the Purbeck strata, with the earliest known Purbeck-type deposition taking place to the north; that there was any continuity between these different depositional areas across southern England is unlikely, but in any case cannot be proved either way.

The climate of 'Purbeck Park'

Allen (1998) with literature contributions from many of those involved in studies on the Purbeck and Wealden strata weighs the considerable range of data available to suggest climate and climatic trends during this interval. In the lower part of the sequence, wind directions alternated between winter easterlies and summer westerlies, but this became predominantly westerly higher in the sequence. The mean annual rainfall was less than <500mm with strong seasonal variation in the lower part of the sequence. During the deposition of the Intermarine Member Allen suggests that the humid belt shifted northwards influencing the climate of 'Purbeck Park', though within these strata there is evidence for at least one episode of north-easterly winds – though for how long these persisted is uncertain.

What did the Purbeck landscape look like?

The south Dorset Purbeck strata were deposited on the northwestern end of what might be called the 'Purbeck Basin', but which would be more accurately described as the Portland-Wight Basin. This extended out into what is now the English Channel. Underhill (2002) has compiled outcrop, subsurface and seismic data to delineate this basin, showing that the Purbeck strata thicken eastwards, from 77.1m in Mupe Bay to 116.9m in Durlston Bay, achieving a maximum of >200m just west of the Needles at the west end of the Isle of Wight. Underhill shows that the basin's northern margin was defined, and the rate of subsidence controlled, by the E-W striking Purbeck Fault which follows the Purbeck-Isle of Wight monoclinal axis, and the more westerly Abbotsbury-Ridgeway Fault. Displacement of this well-defined E-W fault zone appears to be linked to the southerly extension of NW-SE trending Watchet-Cothlestone Fault. To the north of these E-W trending faults, Underhill identifies an area of non-deposition or erosion, previously suggested by myself (Ensom 1985a). One can speculate that our Purbeck landscape if viewed from the south would have been a relatively shallow basin of uncertain westerly, southerly and easterly extent, with a series of fault escarpments on its northern edge. The westward extent of deposition of the Purbeck strata is not known, though sediments are currently preserved as far west as the Isle of Portland and at Friar Waddon and Portesham to the north of Weymouth. The controlling influence on this westerly area of deposition was the uplift to the west, the result of the North Atlantic rifting which gave rise to the prominent mid-Mesozoic unconformity which is so dramatically seen in the coastal sections of western Dorset.

The sedimentary environments in which the Purbeck sediments were deposited reflect these ongoing tectonic controls. The lower Purbeck hypersaline coastal flats and lagoons with evidence of arid salt-flats and sabkhas give way to increasingly brackish and freshwater conditions through the Middle and Upper Purbeck Beds. These deposits show evidence for the increasingly freshwater conditions and are overlain by the clastic-dominated sediments of the overlying, largely fluviatile, Wealden. The sands, grits and clays of this latter formation were laid down in river channels and as over-bank deposits, representing a period of maximum uplift and associated erosion, combined with increasingly wet climatic conditions (Allen 1998). Radley (2002) provides a valuable discussion on what controlled the salinity of the Purbeck water-mass previously recognised by Clements (1973). Radley refers to Closed and Open Associations. The former he associated with the Lulworth Formation (Caps – Cherty Freshwater Member = Lower – lower-Middle Purbeck Beds) and the latter with the Durlston Formation (Cinder – Upper Cypris Clays and Shales Member = middle-Middle – Upper Purbeck Beds). The former he associates with a strongly seasonal climate, arid summers and wetter winters and no normal marine influence. Conversely Radley suggests that the Open Association was the result of either marine incursions or seeps from the marine environment through beach barriers. Faunas are more restricted in the Closed system and at times more varied in the Open systems. I find it fascinating, and presumably far from a coincidence, that the Closed systems have substantially more micritic sediment present than the Open systems. The Corbula Member lies within the Durlston Formation and is significantly more micritic, sharing other features in common with similar strata in the Lulworth Formation: I touch on this later.

How the gross framework of the landscape changed throughout Purbeck times is not easily deduced. Was there always 'high' ground to the north of the fault line – or were there periods when deposition took place over and to the north of this fault-controlled boundary? The presence of derived, silicified ostracods from the lower Purbeck Beds in the Scallop Member (Clements 1986) does point to reworking of earlier deposits, but this could of course be intra- rather than extra-basinal; an example of this is given by Radley (2002) who points to the reworking of oyster shell in the members above the Cinder Member. He suggests that the exhumed or unburied Cinder Member is just that source!

'Purbeck Park' Chapter 1: Hot and hostile – The Lower Purbeck Beds.

The Lower Purbeck Beds consist of the following members: Caps, Broken and Dirt Beds, Cypris Freestone, Hard Cockle, and Soft Cockle.

The retreat of the Portland sea, with its rich fauna of molluscs including the massive ammonites such as *Titanites* and *Glaucolithites*, and other marine fossils heralded the birth of 'Purbeck Park'. The lower beds are dominated by algal stromatolite limestones, thinly bedded limestones, including many composed of faecal pellets, with small-scale ripple-drift lamination,

ripple-marked surfaces, halite pseudomorphs and abundant evidence of the former presence of evaporites (West 1975), and including the dramatic collapse structures within Cypris Freestone Member lithologies and known as the 'Broken Beds'. The concentration of halite pseudomorphs at some horizons and extraordinary strings of crystals which align themselves along the axes of the hopper-shaped single halite crystals, can be observed on salt flats on Cyprus today. This would have been a harsh, arid and blindingly bright environment.

Despite this apparently inhospitable environment, unequivocal evidence for the presence of dinosaurs has been found. When I left Dorset in 1989 I had kept a watching brief for many years but had not found any evidence of dinosaur tracks so low in the sequence. This was soon to change as during the 1990s, Jane Francis spotted *in situ* tracks in basal Purbeck sediments on Portland. More recently, a considerable concentration of dinosaur tracks at a slightly higher level has been found amongst quarry waste, also on Portland. These finds provide concrete evidence that this area was connected to a hinterland which supported populations of dinosaurs. My own work on the new Portland site has shown that several species were represented including tridactyl bipedal track-makers and a much larger sauropod. This latter group is represented by one extraordinary footprint around 1 metre long, though the possibility of overlap between the hind and front foot in this one print cannot be ruled out. The recent discovery of a single incomplete metatarsal of a slightly smaller sauropod adds colour to this situation. Found in a neighbouring quarry, the bone appears to have come from the same or an adjacent horizon in the sequence! Watch this space!

Figure 1. Fossil Forest, Lulworth Cove. a) Algal stromatolitic burr which had grown around the base of the inundated conifer; b) Dirt bed or palaeosol.

The basal Purbeck strata in the west (Portland, Portesham and Lulworth Fossil Forest) are famed for their palaeosols – or dirt beds (Figure 1b), though in some cases these are reworked soils, and the fossil plants they supported. A variety of different coniferous tree elements were collectively described by Jane Francis (1983) under the name *Protocupressinoxylon purbeckensis*, and 'cycadophytes' represent a flora adapted to dry, sparsely vegetated savannah-like conditions (Francis 1983). Many of these remains are silicified. Spectacularly, the trunks of these Purbeck conifers are often found surrounded by masses of algal stromatolite (Figure 1a). The inundation of these Purbeck forests by the hypersaline water of the Purbeck lagoons has been considered to be nothing more than the result in fluctuations in the water levels. Underhill (2002) presents a more dynamic scenario: he suggests that the rapid submersion of these conifer trunks and their branches was the result of catastrophic inundations of the sparse, low-lying and lagoon-fringing conifer 'forests' as a result of sudden downward movement along the southern side of the Purbeck Fault. The forests were killed by the hypersaline lagoonal waters, the trunks and branches becoming perfect attachments for the omnipresent algae. Often all that remains today of these conifers is an empty ring of algal stromatolite: the visiting Victorians and Edwardians were almost certainly responsible for the selective removal of the silicified conifer wood! The preserved microflora indicates the presence of additional species but the identity of the plants from which these remains originated remains uncertain. There is some evidence for small-scale fires in the ground covering vegetation (Allen 1998).

Fauna tends to be species-poor but often high in numbers, indicative of the stressed environments which existed at this time. Ostracods are often abundant as elsewhere in the sequence. The evaporites remain a common feature into the Soft Cockle Member where at Worbarrow Tout, large masses of gypsum fallen from the cliffs are usually present on the foreshore. Above this horizon, beds of replaced evaporites continue to be a common occurrence. These deposits are the product of sabkhas which are common today along the north African coast and around the Gulf states. The limestones are generally fine-grained micrites with interbedded clays, shales and relict evaporites. Insect remains are well known at certain horizons, their delicate structures being perfectly preserved in this near-perfect casting medium. One may envisage dry and dusty flats with occasional pools of water ready to trap the remains of these creatures as they blew across these desolate wastes. Vertebrate remains include scatters of fish remains, and a small fragment of a pterosaur bone has also been found. Ephemeral pools or lakes occasionally developed in the deeper parts of the basin. At Worbarrow Tout thinly laminated shales contain the remains of conchostracans. These small bivalved arthropods' life cycle is linked to seasonal flooding by fresh, or possibly slightly brackish, water. The eggs require desiccation before their hatching is triggered by wetting. These finely laminated shales along with their fauna point to a seasonal, varve-like deposit. Other arthropods are known from the Purbeck sequence, perhaps best amongst them are the remains of the isopod *Archaeoniscus*, looking like a large woodlouse and on occasion occurring in large numbers on an individual bedding plane! Less

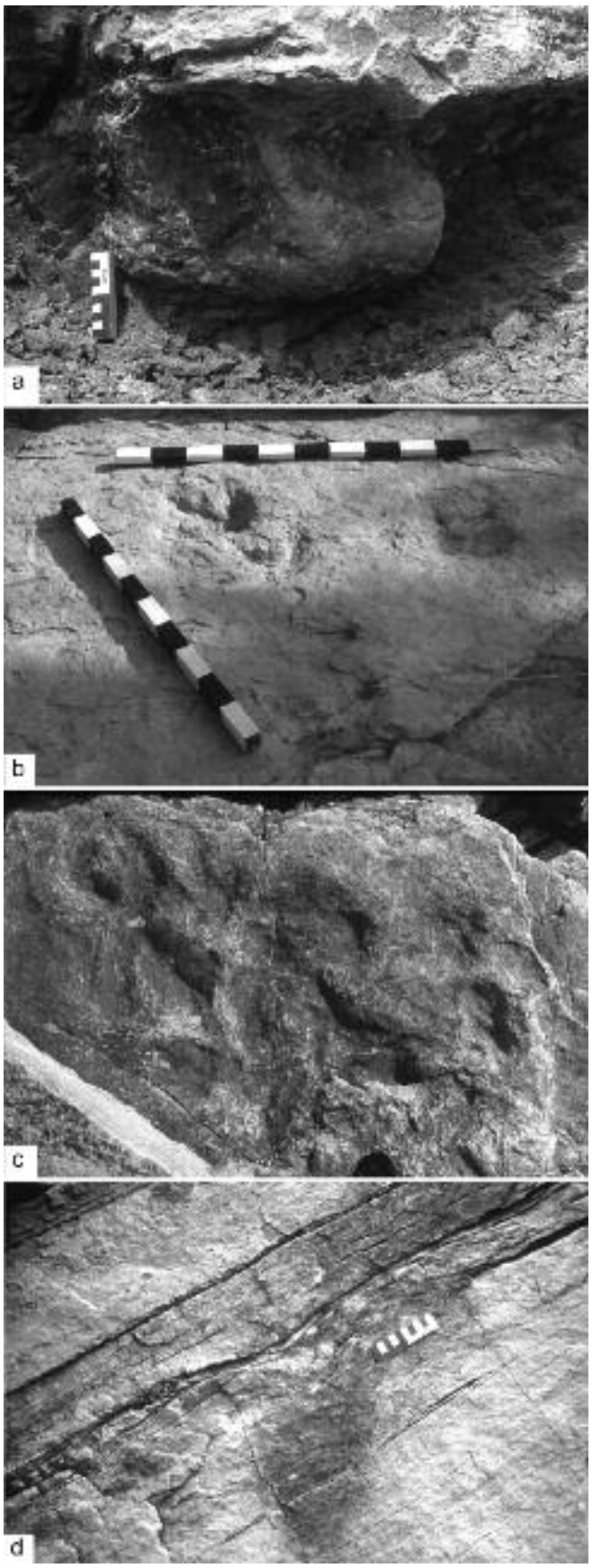

Figure 2. a) The *in situ* cast of a large footprint (pes) of a quadrupedal dinosaur (Sauropod or ankylosaur?) on the base of the Cap, Cherty Freshwater Member, at Sunnydown Farm Quarry, near Langton Matravers 1986. Scale bar 0.1 m; b-d) All from Laning Vein, Intermarine Member. b). Trackway of ?theropod, showing change of direction, at Townsend Road, Swanage, 1981. Scale bars 1 m; c) Dino-trampled bedding plane at Worbarrow Tout. SLR lens cap for scale; d) Dinosaur footprint seen in section with associated distortion (transmission of footprint) of the strata below the surface on which the footprint was made. Same horizon as c at Worbarrow Tout. Scale bar 0.1 m.

obvious but incredibly abundant are the aquatic ostracods. They have been used for stratigraphic purposes, but there is an ever-lingering concern that they are sensitive to environmental conditions; while useful in intra-basinal correlation, they are unlikely to be entirely reliable. Their greatest value is as indicators of salinity. Horne (2002) provides a valuable review of both the group and previous studies.

'Purbeck Park' Chapter 2: Out of the frying pan into the …..? The Middle Purbeck Beds.

The Middle Purbeck Beds have traditionally included the following Members: Marly Freshwater, Cherty Freshwater, Cinder, Intermarine, Scallop, Corbula, and Chief Beef.

While the lowest beds of the Middle Purbeck Beds continue to echo the micrites and shales/clays of the Soft Cockle Member, there are real signs that the environment is becoming more amiable. An event of considerable significance on our visit to 'Purbeck Park' is the opportunity to observe the mammal-bearing sediments being deposited which Samuel Beckles was to excavate in 1857 following the suggestion of Richard Owen that he should prospect for the evidence of these diminutive and still primitive mammals. Charles Kingsley (1857) who was visiting Swanage at the time wrote a marvellous description for the Illustrated London News, describing Beckles' monumental excavation in the cliff and in the process did much to boost the level of public interest in these strata. Collective wisdom has it that his excavation targeted a layer of sediment close to the base of the Marly Freshwater Member on the cliffs in Durlston Bay. Problematically, the matrix of the specimens he obtained does not match that of the present outcrop of this horizon! Of course there may be significant lateral variation along the outcrop of this bed or he may have found a lens of sediment quite different from the rest of the bed, but there remains a distinct possibility that another horizon may have been the real source of his remarkable collection. This is an issue currently being looked into by my colleague Ms Sandra Chapman and myself at the NHM where Beckles' Collection is one of our key and much used collections. The importance of the collection has much to do with the fact that the remains recovered by Beckles consist of the maxillae and mandibles, often with reasonably complete dentitions. He also collected the remains of lizards, crocodiles, turtles and dinosaurs, one of which was later named in his honour, *Echinodon becklesii*. A few years before, a local surgeon had found a tiny dinosaur jaw and some bones which at the time were linked to the specimen. The jaw was described by Richard Owen as the type specimen of *Nuthetes destructor* which has subsequently been regarded as a variety of Megalosaur. This specimen and additional teeth in the collections at the NHM have been re-described by Angela Milner (2002) as belonging to a dromaeosaur, the first record from Britain. The bones which Owen had tentatively associated with the jaw are more likely to belong to one of the larger lizards, and some small tuberculate granicones, a type of dermal armour, have been associated with turtles (Barrett *et al.* 2002). There remains considerable uncertainty over

the stratigraphic sources of much of the earliest vertebrate material obtained from these strata; collecting was 'complicated at the time' by the lack of detailed logs and through the use of quarryman's terms for the various beds - and even locations! More recent collecting at all levels within the Purbeck Limestone Group has had the advantage of detailed logs (Clements 1969 & 1993, Ensom 1985b) which have allowed a far greater degree of resolution.

The overlying Cherty Freshwater Member, which may have been the source of some of the above specimens, has certainly become the focus of much recent work. This member, so named because of the prominent beds of chert (an often black, flint-like rock) in the micrite is one of the lowest that the 'Purbeck Plateau' quarrymen (those operating between Worth/Langton Matravers and Swanage) have extensively quarried for the quality stones it contains. This has of course provided excellent opportunities for observing and collecting. A visit to a small quarry near Langton Matravers in 1986 led to a series of discoveries which are still fueling research both here in the UK and elsewhere. Excavations of a significant dinosaur tackway site discovered at Sunnydown Farm in 1986/7 led to the discovery of a vertebrate-rich clay which has turned out to be extraordinarily productive, and which has stimulated a renaissance in Purbeck studies. The vertebrate fauna from this bed includes fish, amphibians which were the first recorded from the Purbeck strata of Dorset and include albanerpetontids, salamanders and a frog, reptiles including chelonians, lizards, sphenodontids, crocodiles, pterosaurs and dinosaurs including both theropods and ornithischians. Finally there are the mammals which are represented by numerous isolated teeth, sometimes occurring in discrete and apparently associated groups, and very rarely in a dentary. Despite the lack of associated dentitions they have enabled a comprehensive review of the mammals (Sigogneau-Russell & Kielan-Jaworowska 2002) of the fauna known from the earlier collection of Beckles and other isolated finds, and in the process added several new taxa to the fauna. These discoveries have led to an ongoing and successful re-examination of the Purbeck beds as a potential source of further mamal bearing horizons. In addition to the body fossils, there were the dinosaur footprints originally discovered which represented several species of bipedal, tridactyl, dinosaur tentatively assigned to the Theropoda and Ornithopoda (the teeth of both are present in the sediments), and a large quadrupedal dinosaur which has variously been interpreted as a sauropod or ankylosaur (Ensom 1987) (Figure 2a). In addition, reptile eggshell was recovered for the first time from the Purbeck beds (Ensom 2002a). Subsequently and using samples from other horizons, eight types of eggshell have been identified representing chelonian, crocodile and dinosaur. Predated or scavenged bone fragments are not uncommon with lacerations, cut and grip marks. Coprolites are abundant and at least some are of a vertebrate origin; the remains of a lizard dentary or maxilla has been found in one! The exact mechanism by which so many microvertebrates came to accumulate in one thin layer remains something of an enigma. A coprocoenosis seems unlikely as the preservation of so much of the material recovered is excellent with evidence of acid etching of enamel surfaces being an unusual feature. Predation on a coexisting population of tetrapods around the periphery of the freshwater lake deposit in which the sediments accumulated (West 1988), a normal death assemblage accumulating over an extended period of time, or even the winnowing and concentration of an earlier

Figure 3. Cinder member (lower picture) overlain with the Intermarine Member. Durlston Bay.

deposit require detailed taphonomic study of the recovered fauna and is an outstanding task associated with the Sunnydown Farm site. Footprints occur at other horizons within this member. Other fauna includes freshwater gastropods, bivalves and the ubiquitous ostracods. Frequently occurring in large numbers are the stems of freshwater charophyte algae which have been detailed by Feist *et al.* (1995). The gyrogonites of these calcareous freshwater plants are exquisitely sculptured spheres; they are abundant at certain horizons.

Before leaving the Cherty Freshwater Member I would like to draw attention to what I believe are karstic horizons. Arguably the most obvious of these occur in this unit in Luworth Cove (pers. obs.), but there are other localities and horizons which seem to show some evidence of dissolution of the limestone surfaces with the dissolved surface overlain by limestone clasts in a darker, soil-like matrix. This example is not unique in this member.

Overlying the Cherty Freshwater Member is the Cinder Member (Figure 3). The base of this oyster- rich micrite was recognised by Casey (1963) as an appropriate point to place the Jurassic - Cretaceous boundary. The fauna though dominated by *Praeexogyra distorta* contains the remains of the regular echinoid *Hemicidaris purbeckenis*, rare cirripede plates (Ensom 1985c), serpulid worms and a single occurrence of the bivalve *Pleuromya* (Ensom 1985d). A small hybonontid fish spine has also been recovered. The bed shows quite clear lithological variation, and perhaps most spectacularly, examples of imbrication of the oyster shells. These are seen at one particular horizon within the lower 'Hard Cinder' (Ensom 1984a), indicating that, at least for a time, there was a strong flow of water over the surface of the oyster-rich sediment. This 'marine' interlude has yet to produce an ammonite!

The overlying beds of the Intermarine Member (Figure 3) are now increasingly dominated by bivalve biosparrudites, which until now had been relatively uncommon. These are occasionally sandy, sometimes appreciatively so, and intercalated by shales

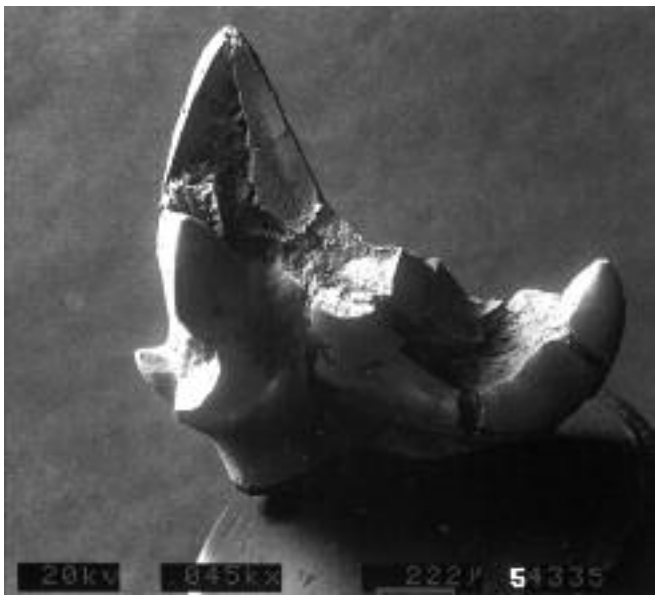

Figure 4. Holotype of *Tribactonodon bonfieldi* (BMNH M51816) Lingual view of a right lower molar of a tribosphenic mammal, Intermarine Member.

and clays with varying carbonate content. Limestones with evidence of dinosaur trackways become common and the majority of the trackways held by both national and local museums have originated from this member (Figure 2 b-d). A comprehensive review and index of discoveries and descriptions up to 1994 (Ensom 1995) provides a useful starting point for anyone wishing to know more about the discovery and description of tracks, water-holes, and features which areeither abundant or rare. The brief description and plan of the trackway site discovered in 1981 at Townsend Road, Swanage, has recently been published (Ensom 2002b). This multiple trackway site is in what in quarryman's parlence is called the Laning (Lane End) Vein at the top of the Intermarine Member. One horizon has yielded what Wright *et al.* (1997) interpret as the tracks and feeding traces of a pterosaur. Associated with one of these footprint horizons is a new mammal fauna, one of two now recorded from the Intermarine Member. This bed is particularly interesting as it shares features in common with the Sunnydown Farm horizon, not least containing a diverse microvertebrate fauna. Unlike the Sunnydown horizon, the mammal teeth are not infrequently found in dentary or maxillary fragments. An exceptional discovery was the molar of a tribosphenic mammal (Figure 4); the first unequivocal specimen from these strata and the oldest known from Laurasia (Sigogneau-Russell *et al*. 2001). Reptile eggshell is also present. At Worbarrow Tout, sediments of what is believed to be the same horizon have been severely disrupted (Ensom 1984b). One interpretation is that it may have been a wallow for larger vertebrates; footprints are associated with this level as at some of the inland sites. A number of horizons within the Intermarine Member contain remains of freshwater charophyte algae.

Enduring questions from my perspective, are how long, and in what conditions, did these beds of limestone take to deposit and where does the clastic sediment originate from? While muddy or micritic partings are present in some of these limestones, others are remarkably free of the finest sediment. A 'muddy' parting does suggest a pause in deposition, a chance for suspended fines to settle, and interestingly they are not uncommonly found associated with dinosaur footprints, but perhaps we are less likely to see evidence of the tracks in the more massive beds and, for that matter, in 'argillites'? Were the massive units of clean limestone sufficiently winnowed over a long period of time, isolated from muddy sediments or deposited at great speed (they generally lack current bedding structures), or even a combination of the first two suggestions? Do the sandy horizons suggest a more energetic transport system from eroding landmasses? Do they indicate periods of renewed uplift, or a source of arenaceous sediment which was only available from time to time - or could it be both? Is there some other explanation?

Shelly limestones remain relatively abundant throughout the Middle Purbeck Beds, though argillites do become increasingly common and thicker higher in the succession. The Scallop Member, which overlies the Intermarine Member, contains a typically marine fauna, and the sandy limestones are often highly bioturbated. There is still an element of doubt as to what the trigger was for this increase in salinity. Despite the uncertainty, the palaeontologist cannot ignore the much wider range of marine species in these strata, including a bryozoan attached to bivalve shell (Ensom 1985e).

The overlying Corbula Member does contain dinosaur tracks, some apparently quadrupedal, just as it also has insect bearing horizons similar to those present lower down the succession. Algal mats can be observed in some horizons and Andrews (1986) has described pseudomorphs after gypsum in one such deposit: there is good evidence that the climate was more arid for at least a time. There are several beds of micrite which probably owe their origin to the wave energy which washed the tiny crystals of calcium carbonate out of the algae and dispersed them over a wide area, a process observed by the late Michael House (1968) on the Great Lakes of North America. Like some of the Lower Purbeck micrites, fossil insects sometimes occur. The molluscan fauna is more obviously interesting with a variety of gastropods often exquisitely preserved on weathered limestone surfaces. Batten (2002) suggests that this is a result of an ongoing marine influence after the almost normal-marine Scallop Member was deposited. Despite this I cannot help but wonder if this is not a return, albeit briefly, to a Closed system like that of the Lulworth Formation. Derived fossils found at the top of the Corbula Member at Worbarrow Tout, provide unambiguous evidence that the Kimmeridge Clay was being eroded (Ensom 1985a) somewhere within the catchment area of this sedimentary basin. Ross Garden (1991) describes suites of pebbles derived from eroding areas in both the Purbeck and Wealden of southern England. The overlying Chief Beef Member in the east of the area is dominated by dark shales and biosparrudite limestones. El Shahat & West (1983) suggest relatively deeper water conditions, though the presence of dinosaur tracks and occasional mudcracks preserved on the base of the limestones is testament to periods of subaerial exposure and desiccation, or water shallow enough to wade in.

'Purbeck Park' Chapter 3: The calm before the storm? The Upper Purbeck Beds.

The upper Purbeck Beds consist of the Broken Shell Limestone Member, Unio Member and Upper Cypris Clays and Shales Member.

At Durlston Bay, the overlying massive Broken Shell Limestone Member forms the prominent cliff running out eastwards to

Peveril Point. This unit is the lowest of the Upper Purbeck Beds. Footprints are present on at least one parting within this bed. Its upper surface is irregular and the Unio Member rests on it. Examination of this bed here and elsewhere along the coast suggests that there may have been a significant event associated with its deposition. Bones of crocodiles and other vertebrates are not uncommon, and as its name suggests, the valves of the freshwater mollusc *Unio* are abundant. At Stairhole, samples have yielded the worn and sadly unidentifiable remains of bryozoans as part of the fauna of derived detritus. It is tempting to speculate that these may be Portlandian in age, derived from uplifted late Jurassic sediments exposed on the up-thrown side of the fault scarp which is likely to have been close by.

Overlying this thin member are the Cypris Clays and Shales Member, famed for the Purbeck Marble, gastropod-rich micritic limestones which are cut and polished and used as a fine, grey, green and red sedimentary 'marble' for decorative work in ecclesiastical buildings such as Salisbury Cathedral, Westminster Abbey, York Minster and in the Galilee Chapel at Durham Cathedral. Many of the limestones in this bed contain the bivalve *Unio* and the gastropod is *Viviparus*, regarded as a freshwater organism. Recently a mammal tooth has been recovered from this member (Underwood & Rees 2002). At Mupe Bay, algal micrites are present. These strata are overlain by the freshwater, fluvial-dominated Wealden sediments. The boundary is not easily seen, but the difference between these two sedimentary regimes could not be more dramatic. Gone are the carbonate-dominated lagoonal/lake sediments, and in come the much coarser clastic sediments of the Wealden. Allen (1998) points to a shift to an increasingly wet climate and associated uplift of the hinterland. 'Purbeck Park' was history and another major chapter in the evolution of Dorset, southern England, and the UK had begun.

However, let the last word be from 'Purbeck Park'! Milner & Batten wrote in the preface to the *Special Papers in Palaeontology* **68,** 'Life and Environments in Purbeck Times' as follows:

> 'One of us (Andrew R Milner) undertook an estimation of the biodiversity of vertebrates that are represented in the Purbeck beds. The remarkable total of 101 described species [already out of date!] of vertebrate was reached, comprising nine elasmobranchs, 26 bony fishes, four amphibians, four turtles, 13 lepidosaurs, seven crocodiles, three pterosaurs, five dinosaurs, two marine reptiles and 28 mammals. No other vertebrate fauna from before the Campanian of North America approaches this diversity.'

Some achievement!

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Book review

Classic landforms of the Coast of the East Riding of Yorkshire by Ada W. Pringle, 2003, Geographical Association, 64pp, £9.99 paperback, ISBN 1843770717.

If you intend to visit the East Riding of Yorkshire, this slim volume is a must. One of a series of "Classic Landform Guides" published by the Geographical Association, it is a mixture of history, geography, geomorphology and geology.

The locations and processes described give us clues to the depositional environments of the past and the present dynamic environment of the East Coast.

The first chapter is a review of the geology of Flamborough Head and the East Riding. Succeeding chapters describe the chalk cliffs to the north and the glacially deposited cliffs south of Bridlington. Marine and coastal processes are described.

I found the history of the deposition and erosion of Spurn Head fascinating. The chapter on "Marine Influences on the Coast" and the explanation of storm surges and waves in the North Sea was particularly interesting.

All the chapters are illustrated with very clear diagrams and colour photographs. There is a useful glossary at the end.

There are clear OS maps and larger-scale sketches to enable you to find your way safely to the various locations. Carparks and coach access are indicated. So if you are going to Yorkshire, or just want to know about it, get a copy!

Mary Howie BA Hons (Open)

Crazy Chalk: Sea-level versus tectonics as a control on lateral variation in the Cretaceous Chalk of the World Heritage Coast of Dorset and south-east Devon

Rory Mortimore, Professor of Engineering Geology, University of Brighton

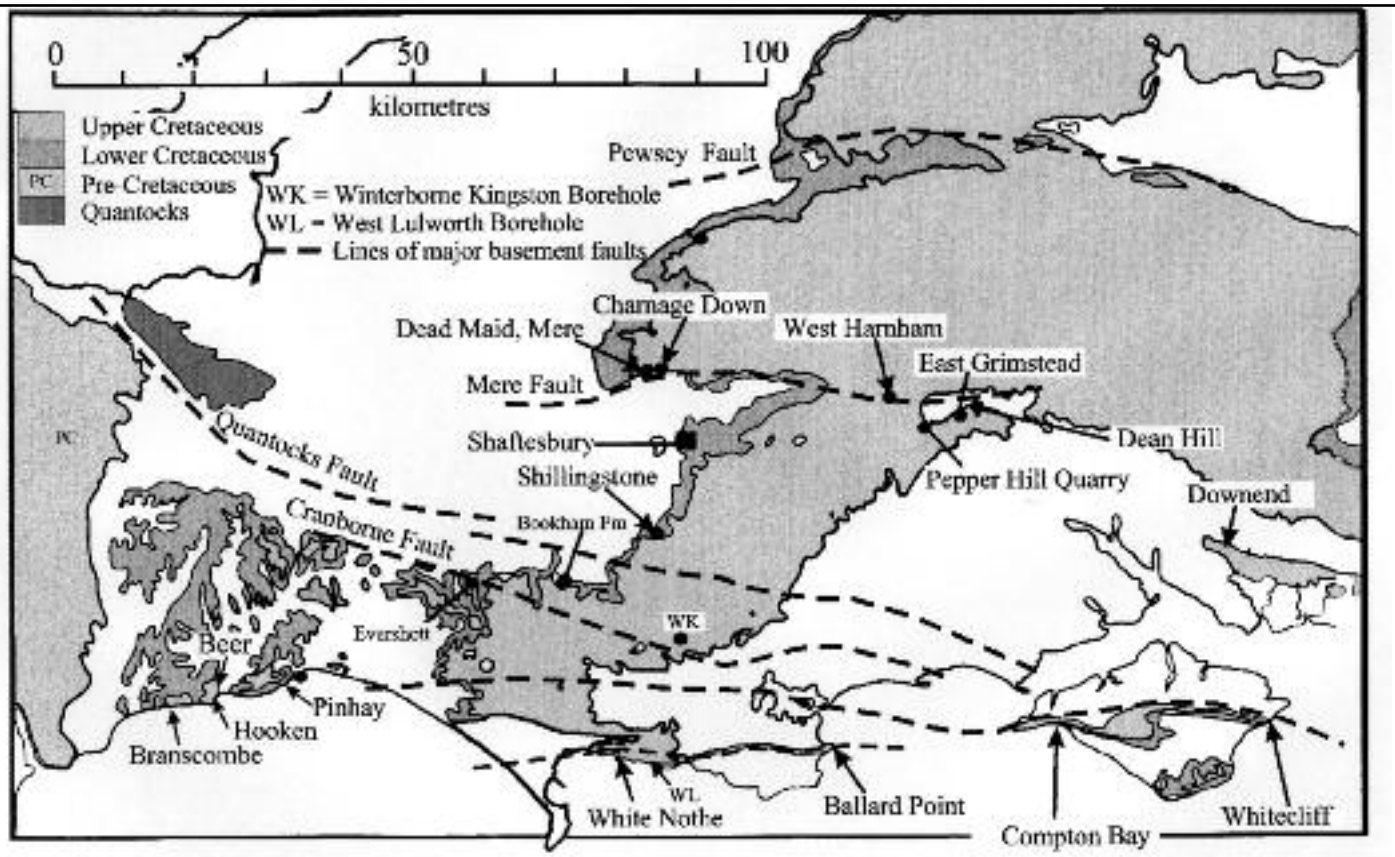

Figure 1. Mid and Late Cretaceous outcrops and localities in Wessex and along the World Heritage coastline of Dorset and South-east Devon.

Abstract

Along the Dorset coast of the Isle of Purbeck, West Lulworth and White Nothe the sea has eroded into folded Chalk to form magnificent cliffs. In contrast, in south-east Devon, faulting rather than folding controls the distribution of Chalk cliffs. In north-west Europe, Late Cretaceous Chalk is the epitome of a former sea-level high, apparently blanketing the continent. Fluctuations in sea-level have been the favoured explanations for intra-chalk erosion surfaces and hiatuses and lateral variation. However there is evidence from the World Heritage coastline that tectonics played an equally significant part in Chalk sedimentation history.

In other parts of the World, such as Israel, the geological setting of Cretaceous and Eocene chalks is intimately related to the edge of the Sinai subplate - Arabian Platform and to strike-slip tectonics along the Dead Sea Rift. Strike-slip has produced a series of *en echelon* periclinal folds (the Syrian Arc structures) which were also active during chalk sedimentation. *En echelon*, periclinal folding is common in the chalk terrains of north-west Europe and is also partly controlled by strike-slip tectonics active during chalk sedimentation. A similar style of folding is present in southern England represented on the Heritage Coast by the Weymouth – Purbeck folds.

This paper illustrates the similarities and differences between north-west Europe, particularly the Heritage coastline of Dorset and south-east Devon, and the Syrian Arc in tectonic style and sedimentation history. The timing of both tectonic and sea-level events in the Late Cretaceous of both regions is discussed.

Introduction

The World Heritage coastline of Dorset and Southeast Devon (Figure 1) is a classic area for the geological study of the Mid-

Series		Stages	Time Span
Upper	65.4	Maastrichtian	5.9
	71.3	Campanian	12.2
	83.5	Santonian	2.8
	86.3	Coniacian	2.4
	88.7	Turonian	4.6
	93.3	Cenomanian	5.2
Lower	98.5	Albian	13.5
	112	Aptian	9.0
	121	Barremian	6.0
	127	Hauterivian	3.0
	130	Valanginian	5.0
	135	Berriasian	7.0
	142		

Figure 2. Cretaceous series and stages with dates and age picks in millions of years from Obradovitch (1994) and Gradstein *et al*. (1999).

and Late Cretaceous (Figure 2) westwards overstep onto older and older rocks as sea-levels rose. This Late Cretaceous overstep has two parts, the earlier part is really mid-Cretaceous (Aptian – Albian, Figure 2) represented by the Gault and Upper Greensand in the coastal cliffs resting on a hiatus that increases westwards. It is the second part that is more familiar and is often referred to as the Cenomanian Transgression (Suess 1906; Cooper 1977; Hancock & Kauffman 1979), represented by the deeper water Chalk which also rests with an increasing hiatus westwards on the underlying mid-Cretaceous sediments and then ultimately on red Triassic sediments west of Beer.

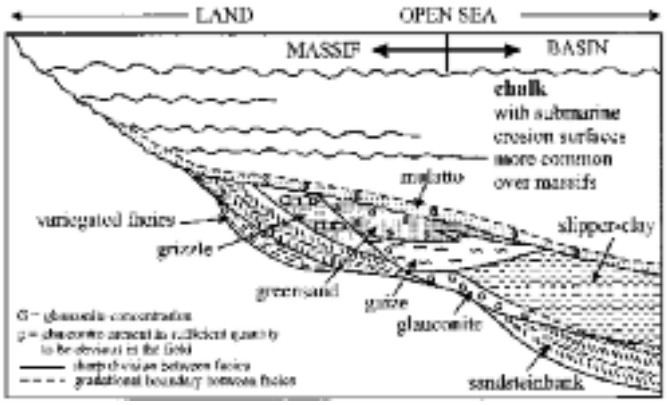

Figure 3. Marginal facies relationships in the Mid- and Late Cretaceous (from Hancock 1975, fig. 4).

At first, a thin succession of dark grey Gault clay (a slipper clay, Hancock 1975; Figure 3) was deposited on eroded Lower Cretaceous Wealden rocks at Punfield Cove and Worbarrow Bay in east Dorset, and then on progressively older Jurassic rocks and ultimately on Triassic sediments in the far west at Axmouth, Seaton and Beer, Devon (Figure 4). Glauconitic greensands with chert beds and other sandy sediments (Jukes-Browne & Hill 1900) follow on the Gault. In the most western exposures of south-east Devon even the Gault thins out and Upper Greensand rests directly on Triassic red mudstones. A second unconformity develops westwards between the Chalk and the underlying Upper Greensand (Figure 4). The deposit at the base of the Chalk on the Dorset coast is the Glauconitic Marl Member, a thin (1 to 2 m thick) calcareous, glauconitic sand full of re-worked (remanié), phosphatised pebbles and cobbles of material eroded out of earlier deposits. As the Chalk-sea transgressed westwards the age of the Glauconitic Marl crosses time (diachronous, Figure 4) and becomes younger. In south-east Devon there is no Glauconitic

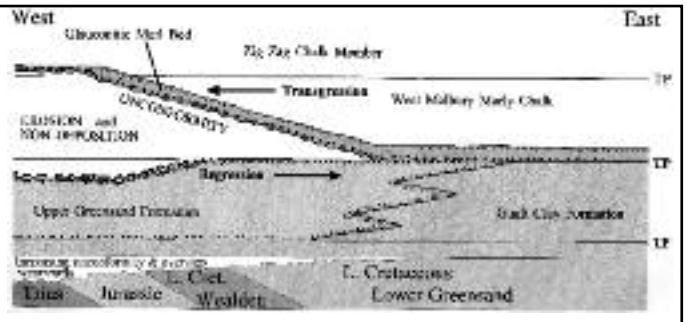

Figure 4. Schematic diagram of the westwards overstep in Wessex of the mid- and Late Cretaceous onto older and older rocks as sea-levels rose.

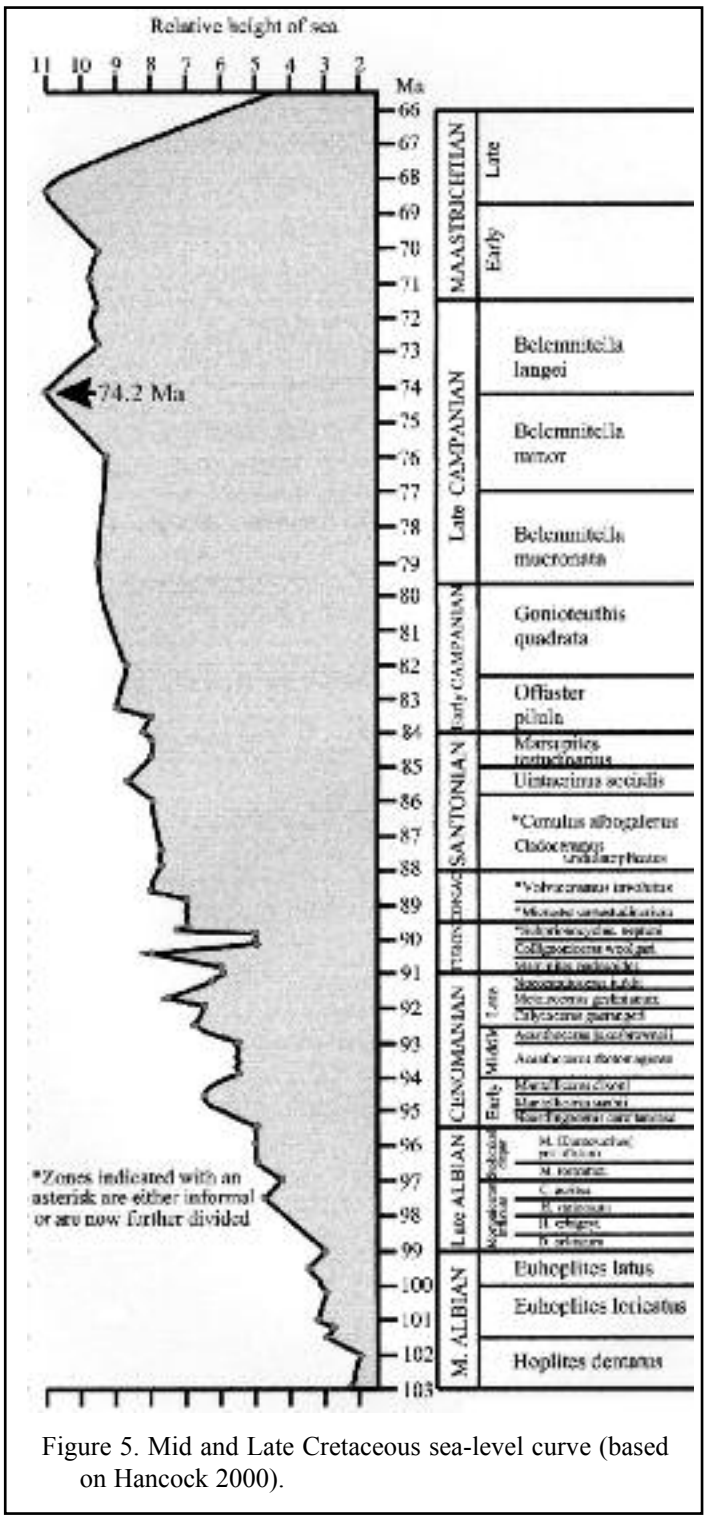

Figure 5. Mid and Late Cretaceous sea-level curve (based on Hancock 2000).

Marl, instead the base of the Chalk is represented by gritty limestones (the base of the Beer Head or Cenomanian Limestone). Eventually the sea deepened sufficiently for carbonate (chalk) to be deposited over the whole region. Sea-levels reached heights perhaps 200-300 metres above present and it was a stepwise increase in depth reaching a maximum in the Late Campanian 74.2 Ma (Figure 5: Hancock & Kauffman 1979; Hancock, 2000). These Late Campanian Chalks are only found in East Anglia but the deepest water chalks of southern England are represented by the belemnite Chalks at Swyre Head and Ballard Head – Studland Bay. Erosion surfaces within the chalk were simply seen as responses to sea-level changes, with more of them occurring over 'passive' massifs (Figure 3). Uplift and folding at the end of the

Late Cretaceous led to erosion of the Chalk (the sub-Palaeogene erosion surface/unconformity) and the return of terrestrial and shallow-marine clastic sediments in the Tertiary.

In contrast to this relatively simple picture of progressive, stepwise deepening of the Late Cretaceous sea, there is increasing evidence of the growth of folds and faults during the Late Cretaceous across the region (e.g. Mortimore & Pomerol 1997) creating a shelf (the Wessex Shelf), a mid-Dorset Swell and local fault-controlled 'troughs' and swells. These tectonic structures influenced the distribution of sediments and erosion surfaces in Wessex and their effects are represented in the coastal chalk cliffs. This paper explores the evidence for the intra-Late Cretaceous growth of these tectonic structures and illustrates how this evidence differs from that indicating sea-level changes or changes in oceanic circulation and climate.

The distribution of sediments in relation to tectonic structure in the Albian-Cenomanian

Although early observers such as Strahan in 1901 had recognised that intra-sedimentary faults existed in the Chalk causing significant and sudden lateral changes in sediment, for example in Mupe Bay and at Lulworth Cove, it was not until the innovative work of Drummond (1967, 1970), that a clearer understanding of the distribution of Albian - Cenomanian sediments in Wessex emerged.

Using isopachyte (lines of equal thickness of sediment) and lithofacies maps, Drummond (1970) demonstrated the presence of a 'Wessex Trough' thickening west to east from the Vale of Wardour to the western end of the Weald. On the north side of this trough a shelf area was present in the Wiltshire-Berkshire Downs, to the south and south-west sediments thinned or were eroded across a NW-SE trending 'swell', thickening again westwards to south-east Devon but with different lithofacies. Hence the 'mid-Dorset Swell', with an axis running through Punfield Cove, separated a Weald - Vale of Wardour region from west Dorset and south-east Devon (Figures 6-9).

An analysis of the known tectonic lines exposed to the west of the Cretaceous outcrop led Drummond (1970, fig. 10) to suggest that there were pulsed tectonic movements on the continuation of these tectonic lines beneath the Mid- and Late Cretaceous

Figure 6. Eo-Cenomanian palaeogeography in Wessex showing the position of the main structural units, the Wessex Shelf, the Wessex Trough and the Mid-Dorset swell, as interpreted by Drummond (1970, fig. 5A).

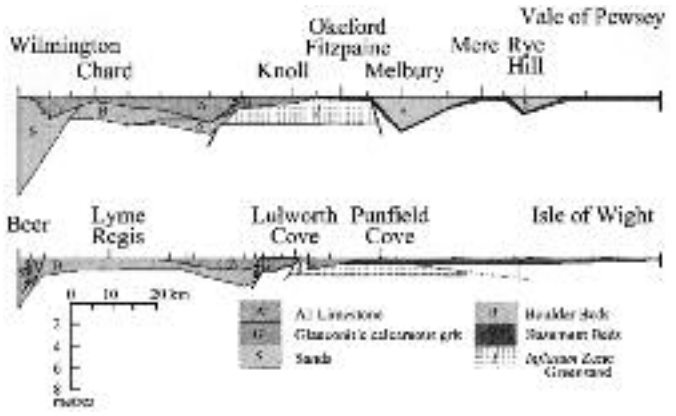

Figure 7. Eo-Cenomanian variation in thickness and lithology in Wessex provides evidence for structural control on sedimentation (based on Drummond, 1970, fig. 5B).

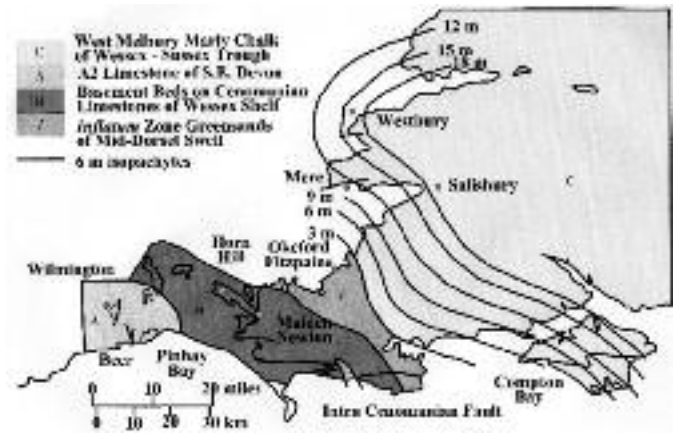

Figure 8. Lower Cenomanian lithofacies, sub-Middle Cenomanian palaeogeology and isopachytes for the West Melbury Marly Chalk Formation in Wessex illustrating continued influence of tectonics on sedimentation in the earliest Late Cretaceous (based on Drummond 1970, fig. 6A).

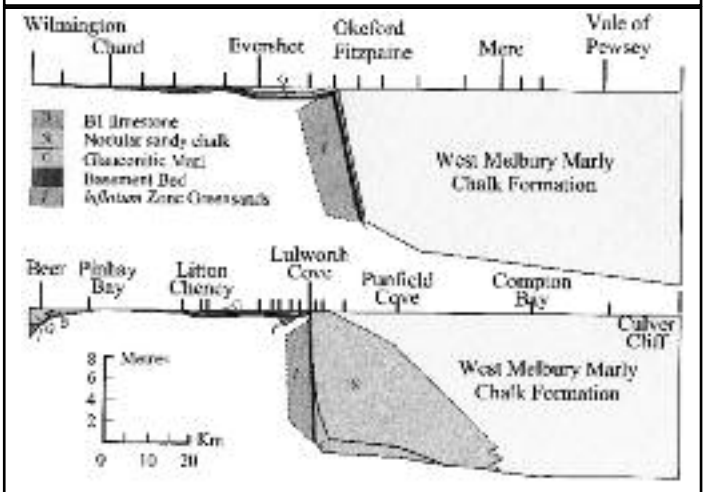

Figure 9. Middle Cenomanian variation in thickness and lithology illustrating impact of tectonics on sedimentation (based on Drummond 1970, fig. 7B).

deposits. These pulsed movements were responsible for: (i) ending *Mortoniceras inflatum* Zone sedimentation; (ii) condensation or erosion of the overlying *Stoliczkaia dispar* Zone sediments in the Upper Albian; (iii) the conspicuous erosional break between the Upper Greensand and the Grey Chalk Subgroup leading to the marked overstep of Upper Cenomanian Chalk on to Albian Upper Greensand in west Dorset. Further tectonic pulses were recognised in the sub-Plenus Marls erosion surface and within the Plenus Marls between Jeffries (1963) Beds 3 and 4. Recent work in inland Dorset has reaffirmed the presence of a Mid-Dorset Swell (e.g. Figure 10).

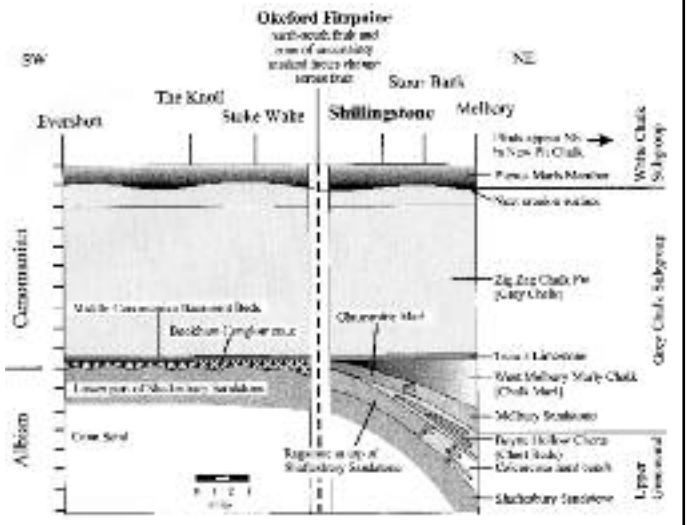

Figure 10. Schematic section showing variation in thickness and lithology in the Albian-Cenomanian interval across the Mid-Dorset Swell (after Drummond, 1970; Bristow *et al.* 1995; Mortimore *et al.* 2001).

In south-east Devon at places such as the Hooken, Beer Head, and Pinhay the Grey Chalk Subgroup (Cenomanian), as chalk, has entirely disappeared and is replaced by highly condensed limestones variously referred to as the 'Chalk with quartz grains' (De la Beche, 1826), 'arenaceous beds' by Jukes-Browne & Hill (1903), which they divided into A, B and C beds. Latterly these beds have been grouped into a unit known as the Cenomanian Limestone (e.g. Smith 1957, 1961, 1965; Drummond 1970). To conform with modern 'Hedbergian' stratigraphical nomenclature the Cenomanian Limestone and its bed divisions are now given geographical, lithostratigraphical names, e.g. the Beer Head Limestone [Formation] Member with named hardgrounds representing Beds A, B and C (Jarvis & Woodroof 1984). This nomenclature has been updated to conform with current British Geological Survey mapping of the Chalk (Mortimore *et al*. 2001).

From Jukes-Browne & Hill (1903) onwards it has been recognised that within the highly condensed Cenomanian Limestones is a laterally variable group of sediments with a stratigraphy representing parts of the expanded Cenomanian Chalk of the main basin to the east on the Isle of Wight and surrounding the Weald. The controversy has been recognising which bits of the Cenomanian are present in the Beer Head Limestone. It is now generally agreed that Jukes-Browne & Hill Bed A is divided by a large hiatus into A1 (Lower Cenomanian *carcitanense* Zone) and A2 (Lower Cenomanian *Mantelliceras saxbii* and *M. dixoni* Zones). A second large hiatus, including a period of erosion and phosphatization, is present between Bed A2 and Bed B, a Middle Cenomanian Limestone. Finally, a third large hiatus with a second period of erosion and phosphatization separates Bed B from Bed C. As recognised by Jukes-Browne & Hill (1903), Bed C is at least in part the correlative of the Plenus Marls.

These condensed, quartz-rich calcarenitic Cenomanian Limestones of Wessex represent periods of sedimentation on a shallow-water marine shelf, probably in close proximity to land (Dartmoor?), interspersed with periods of erosion and phosphatization. The sediments, in terms of composition and age, are very different to those exposed in the Cenomanian parts of the Chalk cliffs on the Dorset coast between White Nothe and Ballard Head (mostly chalks or marly chalks). The periods of erosion and phosphatization would now be interpreted as major sequence boundaries, difficult to recognise in deeper-water chalks of the main basin to the east but tectonically enhanced on the basin margins. In recent studies more evidence has emerged for the tectonic controls on sedimentary variation within the Cenomanian Limestone of south-east Devon at the Hooken. A north-south fault controlled Hooken-Wilmington Trough causes significant lateral changes in thickness and sediment type (Figures 11-12) at the Hooken (e.g. Mortimore *et al*. 2001).

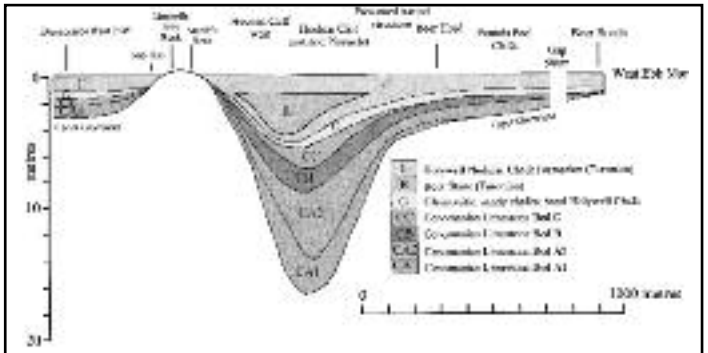

Figure 11. Schematic and simplified view of lateral variation in the Cenomanian and early Turonian deposits of Hooken Cliffs and adjacent areas taking the West Ebb Marl as datum (from Mortimore *et al.*, 2001, fig. 3.21).

The distribution of sediments in relation to tectonic structure in the White Chalk (Turonian to Campanian)

It took a further 15-20 years after Drummond's work for the evidence to emerge for tectonic movements affecting the 'White Chalk'. Even now the ideas are controversial and can only be fully appreciated by bringing in evidence from outside the Wessex coastline.

In south-east Devon, lateral variation in thickness and lithology within the Holywell - New Pit - Lower Lewes Chalk formations show similar patterns to that seen in the underlying Cenomanian Limestone in the Hooken (Figure 13). The very unusual Beer Stone, a calcarenite of fragmented micro-crinoid plates, forms a lenticle within the locally developed Hooken-Wilmington Trough. The New Pit Chalk Formation overlaps the Holywell Chalk westwards onto a structural high known as the Branscombe Mouth Ridge (see Mortimore *et al.* 2001). There are similarities and differences in the Holywell and New Pit Chalk successions of south-east Devon compared to the Chalk cliffs of the Dorset coast at White Nothe, through Mupe Bay to Ballard Head. The similarities include the widespread occurrence of marker beds of marl

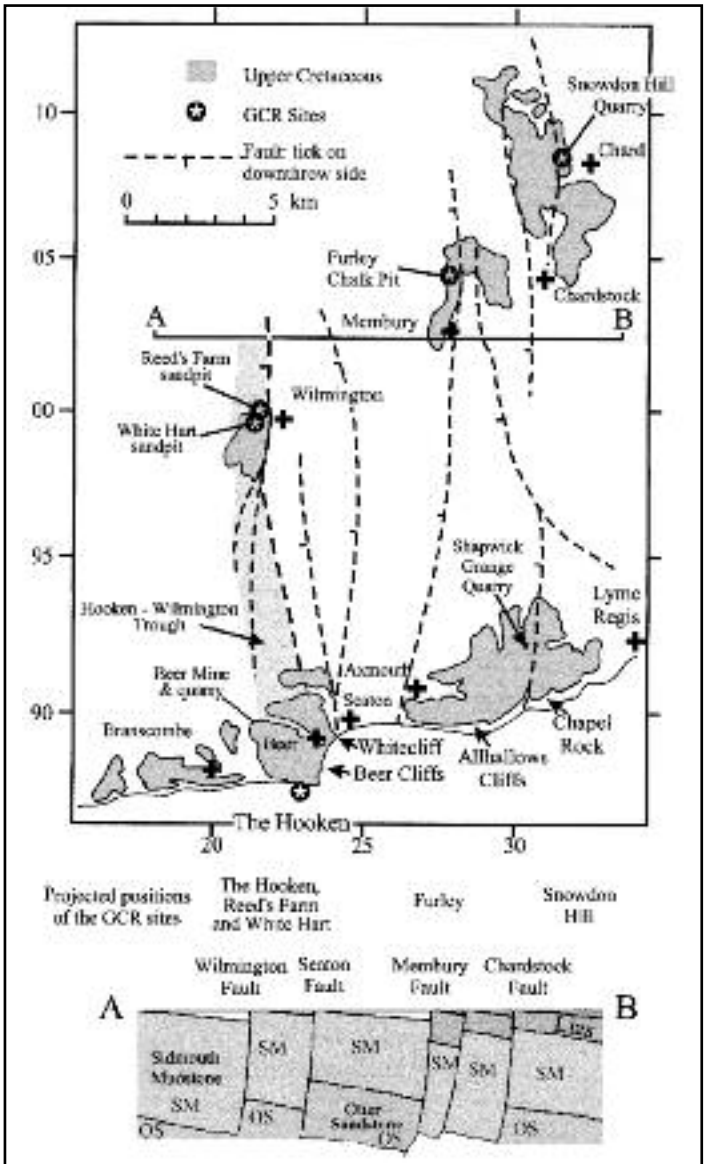

Figure 12. Geological sketch map and section showing the position of the Cenomanian – early Turonian Hooken – Wilmington Trough in relation to north-south faults in the area and illustrating fault control of sedimentation (from Mortimore *et al.* 2001, fig. 3.19).

seams including the New Pit Marls 1 and 2 and the Glynde Marls, forming conspicuous pale bands or grooves in the cliffs at Beer Head and Hooken Cliff. These marker beds, combined with the inoceramid bivalve fossil evidence (particularly the *Mytiloides subhercynicus* and *Inoceramus cuvieri*), allow a detailed stratigraphical analysis of the age of the periods of onlapping and tectonic movement illustrated in Mortimore *et al.* 2001, fig. 3.22. Some of the differences include a New Pit Chalk formation full of flint at the Hooken in contrast to a largely flint free New Pit Chalk in the main basin to the east and in the Dorset coast cliff sections. The reasons for abundant flint relate to organic productivity and water circulation and are mirrored in the cliffs of the French coast at Tilleul Plage, Pays de Caux, also on the southern margins of the Anglo-Paris Basin (Mortimore & Pomerol 1987).

A feature of the Lewes Nodular Chalk Formation is its spectacularly nodular character in Wessex, especially in south-east Devon. The rough, nodular bits stand out in the weathered cliff faces and

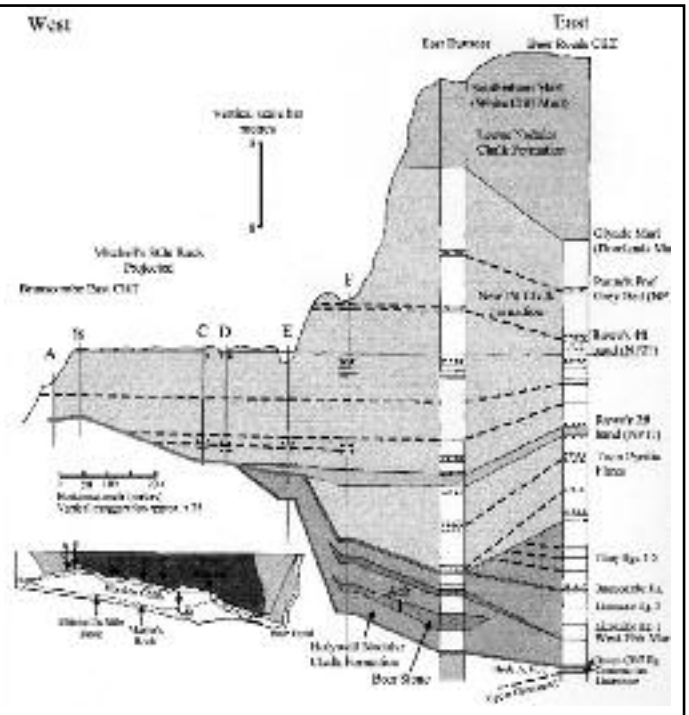

Figure 13. Overstep of the Upper Cretaceous Chalk (Turonian) onto the Albian Upper Greensand in the Hooken Cliff area of the south-east Devon coast (from Mortimore *et al.* 2001, fig. 3.22).

the formation is generally condensed compared to Sussex. Nevertheless, key marker beds including the vulcanogenic marls, in the Late Turonian (Glynde 1, Southerham 1, Caburn, Bridgewick 1 and Lewes) of the north-west European correlation framework, are present in the Dorset and south-east Devon cliffs. Associated with the Lewes Marl is the remarkable Lewes Tubular Flint succession, which apart from areas of extreme condensation in the Chalk Rock of the Wiltshire-Berkshire-Chilterns shelf, are present throughout the Anglo-Paris Basin. Higher in the Lewes Nodular Chalk are the Cuilfail and Beachy Head *Zoophycos* beds present in the coastal cliffs from Ballard Head to the Hooken and correlatable over much of the Chalk of north-west Europe. The Lewes Tubular flints are conspicuous in fallen blocks at Punfield Cove and Worbarrow Bay. At Punfield Cove these fallen blocks contain an abundance of regular echinoids not seen in the main basin to the east indicating local ecological conditions.

In the higher part of the Lewes Nodular Chalk at White Nothe, hardgrounds formed on erosion surfaces along the floors of channels are present, above which are onlapping sediment fills (Mortimore & Pomerol 1987). As similar horizons of the same age are present on both the shelf areas of the French coast in the Pays de Caux, and in places where the Chalk overlies tectonic axes (Mortimore & Pomerol 1987, 1991, 1997), the White Nothe occurrences are interpreted as partly resulting from early growth tectonic movements on faults beneath the Weymouth Anticline.

Higher successions in the Chalk are either not preserved on the coast of south-east Devon or are largely inaccessible in the high chalk cliffs of Dorset. Where the details have been recorded a feature consistently present is the increased size and concentration of flint compared to the main basin to the east. For example, the Seven Sisters Flint Band at Ballard Head develops very large potstones (Mortimore & Pomerol 1987). In the BGS West Lulworth

Borehole, there are hints of disturbed, slumped beds in the Newhaven Chalk Formation similar to those recorded at Whitecliff, Isle of Wight (Mortimore & Pomerol, 1987, 1997).

Evidence for Late Cretaceous growth tectonics outside the Wessex region

From the above descriptions it seems that the Late Cretaceous sea in Wessex transgressed onto a low-relief topography of shelves and local troughs, constantly reactivated by underlying fault movements (growth tectonics). A shoreline may have existed towards Dartmoor. The first sediments of the Mid Cretaceous were sandy, current-swept, near-shore deposits of greensands, cherts and glauconitic marls deposited in three distinct depositional settings, a Wessex Trough, a mid-Dorset Swell and a Wessex Shelf. As the sea deepened and chalks blanketed the region the tectonic lines continued to move leading to locally 'anomalous' periods of chalk sediment. Tectonic growth of these structures through the Cretaceous - Tertiary boundary and on into the Miocene ultimately produced the spectacular folds we now see forming the Purbeck Hills and Chalk cliffs of Dorset and the Isle of Wight.

Are there places elsewhere in Europe that support the idea of growth-tectonics during the Late Cretaceous? Using isopachyte and lithofacies maps Mortimore (1983), illustrated that for the whole of southern England the Late Cretaceous Chalk was deposited in a Wessex-Sussex Trough with its axis running through Salisbury-Winchester and along the northern margin of the South Downs. This trough was surrounded by areas of shallowing and condensed successions: a Wessex Shelf to the south-west and a Berkshire-Chilterns Shelf to the north and west. A mid-Dorset Swell continued to influence Chalk sedimentation. Within the trough and on the shelves local variations in thicknesses and lithology matched the shapes of periclinal folds or local faulted half grabens. This was further illustrated in detail for the South Downs (Mortimore, 1986a,b). Subsequent work across the whole of the Anglo-Paris Basin and in the UK offshore (Badley *et al.* 1989, Mortimore & Pomerol, 1987, 1997), confirmed the influence on Chalk sedimentary history of tectonic lines. These lines included the Pays de Bray Fault, fault bounded blocks such as the Pays de Caux on the French coast and faults underlying folds (e.g. the Kingston Anticline at Lewes, Sussex). The area around Lewes in particular, provided the strongest evidence to support the ideas (Mortimore & Pomerol 1991, 1997). This evidence came from the presence of numerous critical Chalk sections illustrating the sediments and the age of 'events' such as channel formation, phosphatization, slumping and lateral variation. The field evidence was supported by an oil company vibroseis section north-south along the Ouse valley which crossed the east-west tectonic structures illustrating the type of faulting beneath the Mid and Late Cretaceous and the inversion thrust beneath the main Kingston anticline.

These studies by Mortimore & Pomerol (1987, 1991) highlighted the influence of different styles of tectonics on chalk sedimentation. North-south faulting emanating from the Morvern Block created local troughs in the Yonne (eastern Paris Basin). Block faulting in Upper Normandy on the Pays de Caux was responsible for major areas of shallowing, conspicuous erosional sequence boundaries, slumping and increased organic productivity (increased flint) on the south-western shelf. *En echelon* periclinal folding in the main basin created a basin and swell submarine topography over which enhanced sequence boundaries and mass sliding developed. The en-echelon pattern of folding and sedimentation was driven by strike-slip along major Hercynian basement faults such as the Pays de Bray and the Grand Faille du Midi. In addition, these studies confirmed the pulsed nature of the tectonism described by Stille (1924). Hence Stille's terminology has been used for these pre-Alpine tectonic events named after German villages or regions in Lower Saxony, Ilsede (Coniacian) and Wernigerode (Santonian and Earliest Campanian). A further phase of tectonism in the Early Campanian, the Peine, was described by Riedel (1940, 1942) also from Lower Saxony. It has taken some 70 years for Stille's tectonic phases to become more widely recognised across Europe (Mortimore & Pomerol, 1997; Mortimore *et al.* 1998).

Evidence for Late Cretaceous growth tectonics from further afield: the Syrian Arc Fold Belt, Israel

Other areas of the world such as the western margins of the Arabian Platform-Sinai subplate, were also tectonically active during Late Cretaceous to Eocene chalk and limestone sedimentation (Freund 1965). This tectonic activity, was partly the cause of spectacular mass transport in Eocene chalk in the Shefela area of Israel and led Buchbinder *et al.* (1988) to refer to the deposits as the 'Crazy Eocene'. The Cretaceous to Eocene carbonates of this region were formed across the actively growing Syrian Arc fold belt (Figure 14; Krenkel 1924; Braun *et al.* 1987; Garfunkel 1988, 1989; Honigstein, *et al.* 1988). Deeper-water slope and base-of-slope deposits, including Cretaceous chalk turbidites,

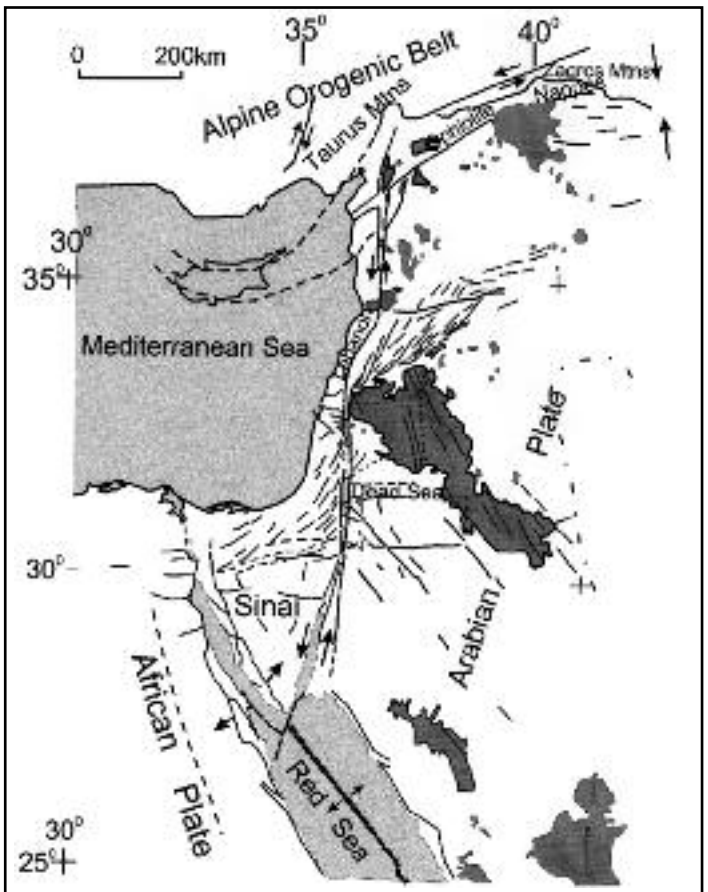

Figure 14. Structural elements in the eastern Mediterranean showing present-day relative plate motions and the NE-SW to E-W trending folds and faults of the Syrian Arc (based on Garfunkel, 1988, fig.1).

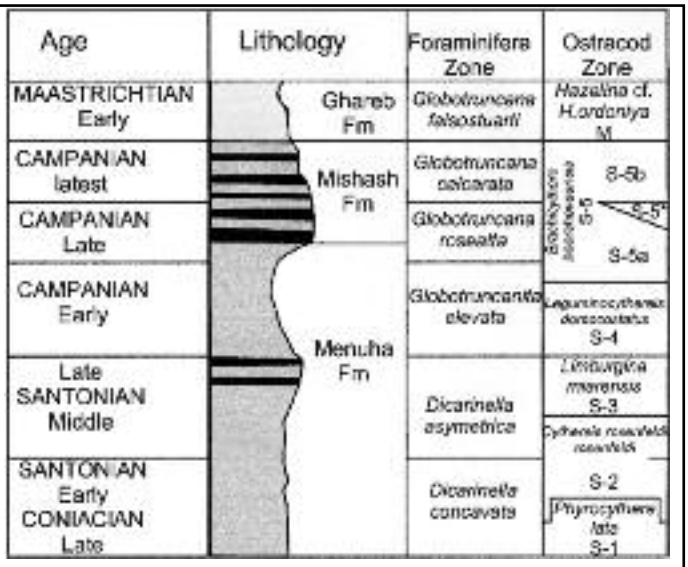

Figure 15. The Coniacian - Maastrichtian succession in Israel and its microfaunal zonation (from Honigstein *et al.* 1988, fig. 1).

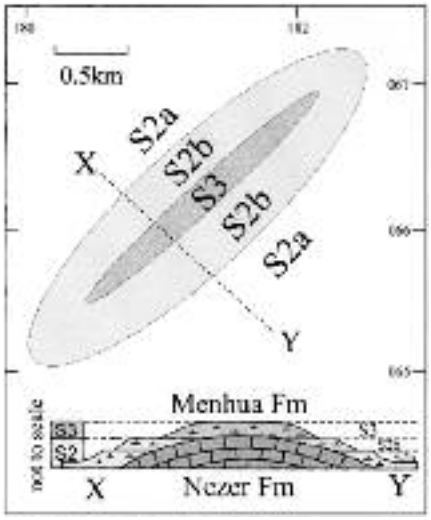

Figure 16. Using ostracod microbiostratigraphy to demonstrate onlap of the Menuha Chalk Formation onto the Zuk Tamrur structure (from Honigstein *et al,* 1988, fig. 4).

were shed westwards off the western flanks of the Arabian Shelf into the Tethys ocean in the Mount Carmel area (Sass & Bein 1982). Chalk turbidites are well exposed at Rosh Hanikra to the north, interbedded with non-turbidite, flint-bearing chalks.

Honigstein *et al.* (1988), and Flexer *et al*. (1989), used ostracod microfossils to determine the Late Cretaceous age of faulting and folding and subsequent rate of onlap of chalk sediments onto the folds in the Negev Desert and Judean Hills (Figures 15-17) within the Syrian Arc. Their summary chart (Figure 18) illustrates the periods of main tectonic activity in the Late Turonian - Coniacian and in the Santonian and Campanian. Lewy (1990) described other tectonic events in the Early and Late Campanian. Lewy went further and supported Jeleltzky (1977, 1978) in suggesting that many of the so-called eustatic events (sea-level changes) were driven primarily by tectonics.

The significance of the model of tectonic growth of faults and folds during the Late Cretaceous in the Syrian Arc fold belt is that

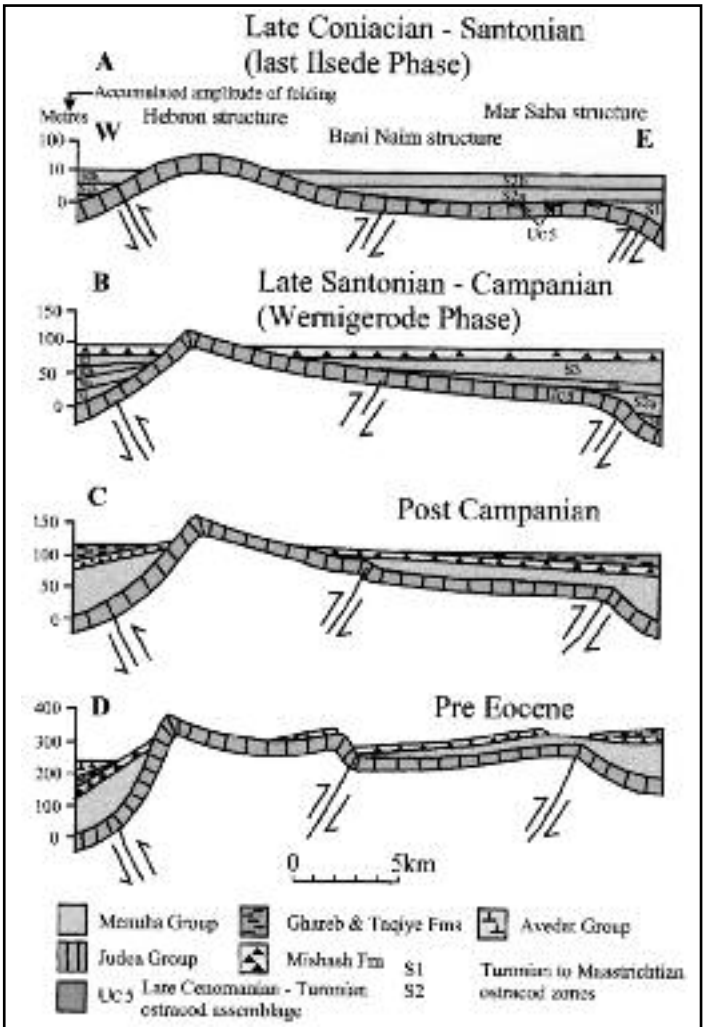

Figure 17. The structural evolution of the Judean Mountains (Israel) by growth faulting and folding during the Late Cretaceous (from Flexer *et al.* 1989, fig. 7).

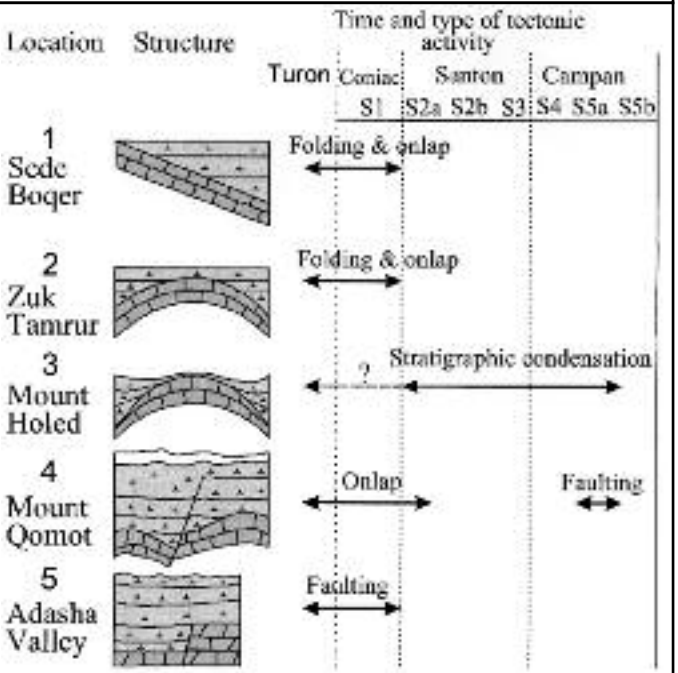

Figure 18. Summary chart of Late Cretaceous – Tertiary growth faulting and folding tectonic in the Syrian Arc in Israel (from Honigstein *et al.* 1988).

it can be used to illustrate lateral variations in thickness and lithofacies in chalk sediments formed during active periods of strike-slip tectonics. In addition, the broad setting on the margins of a cratonic platform illustrate what happens to chalk sediments on a downwarping ramp area (Buchbinder *et al.* 1988, Föllmi 1989). This model has many parallels with Late Cretaceous Chalk sedimentation in the Anglo-Paris Basin. Reiss (1988) used the growth-of-folds model to illustrate how different carbonate and chalk sediments (including phosphorites and cherts/flints) could have originated on a slope and shelf on the edge of the Tethys ocean. His model can readily be applied to the Anglo-Paris Basin.

Discussion

In recent years the global sea-level curves of Haq *et al.* (1987, 1988) and sequence stratigraphy have persuaded the geological community of the pre-eminence of eustatic processes as a means of global correlation. In carbonate successions such as pelagic chalk, sea-level in particular seems an obvious control on its distribution and any variations present. However, Jeletsky (1977, 1978) illustrated how tectonics had a major control on sedimentary cycles and lithological breaks in the Cretaceous of Canada. More recently Lewy (1990), separated sea-level events from tecto-eustatic events on the Cretaceous shelf of Israel and adjacent countries. In so doing Lewy pointed out that much of the calibration for the purely sea-level curves was based on continental areas such as the Arabian Platform and North America where he and others recognise tectonism as a major control on the 'sequences'. A further debate exists about the driving forces causing the folds to 'grow'. In the past these have been referred to as 'compressional' forces (Van Hoorn 1987; Ziegler 1987a&b) with no clear idea of how the stresses were transmitted and localised to the growth of the assymmetyrical *en echelon* anticlines that are typical of the Anglo-Paris basin and the Syrian Arc.

The evidence presented above for the controls on lithofacies, sedimentary breaks and thicknesses (isopachytes) in the Mid and Late Cretaceous of the Anglo-Paris Basin (including Wessex) shows strong parallels with the Syrian Arc of the Arabian Platform. Growth of faults and folds during the Upper Cretaceous, leading to erosional surfaces, hiatuses, and condensed sections appears to be driven in both regions by strike-slip fault movements. There is also a strong similarity in the timing of the major events and these closely correspond to the Subhercynian tectonic phases of Stille (1924) and Riedel (1938, 1940, 1942) reinvestigated Kockel 1986, Betz *et al.* 1987, Baldschun *et al.* 1991, Niebuhr 1995, Neibuhre & Ernst 1991) and applied to the Anglo-Paris Basin by Mortimore & Pomerol (1997) and Mortimore *et al.* (1998). In both regions there appear to be more Late Cretaceous tectonic events than those included in the Subhercynian phases, particularly in the Cenomanian and Turonian.

Similarity in timing of tectonic events beyond a local area or region has generally been considered to be unlikely. Only sea-levels are considered to have synchronous global impact (Hancock & Kauffman 1979; Haq *et al.* 1987, 1988; Hancock 2000). However, the evidence from the Arabian Platform and north-west Europe suggests that widespread tectonism of a similar age can occur across cratons. Far-field effects of tectonic stresses are beginning to be more widely recognised (Bosworth *et al.* 1999) and one Late Cretaceous event, the Late Santonian - Early Campanian - Wernigerode phase has generated major erosional hiatuses, folding and faulting around and across the Afro-Arabian plates (Guiraud & Bosworth, 1997), and across north-west Europe. Such a far-field effect has been interpreted as resulting from a shift of >20° of arc of the poles of rotation of Africa relative to Eurasia with concomitant change in Eurasia-Africa relative motion changing from sinistral and transtensional to dextral and transpressional (Bosworth *et al.* 1999). This idea of a change in lateral strike-slip motion supports the change in stress field for Europe recognised by Ziegler (1987, 1990) and used by Mortimore & Pomerol (1987, 1997) to explain some aspects of anomalous sedimentation in the Chalk.

Conclusions

The debate on the different impacts that sea-level and tectonism have had in terms of generating sedimentary erosion surfaces, hiatuses, condensed sections and sedimentary structures such as slumping and debris flows continues. This debate is well illustrated by the different interpretations of such structures in the Late Cretaceous Chalk. Sea-levels are generally seen as the only earth-bound global process capable of producing world-wide sedimentary events. Certainly sea-level changes have had a marked effect on the coastal geology of the World Heritage Coast of Dorset and SE Devon. One of the most profound sea-level rises led to the Cenomanian Transgression (in the terms of Suess 1906 and Hancock & Kauffman 1979) of the Late Cretaceous. This transgression resulted in most of the British Isles being submerged and to the deposition of Chalk on many continental areas and ultimately to the formation of the Chalk cliffs of Dorset and Devon. Within this succession onlapping sediments reflect this progressive sea-level rise. However, within what appear to be homogeneous white chalks are many variations, some reflecting sea-level fluctuations, others reflecting tectonic episodes.

The wonderful folds that give the Dorset coast its distinctive character, with steep dips of beds to the north at Ballard Head, Worbarrow Bay, Mupe Bay, Lulworth Cove, Durdle Door and Swyre Head were not simply formed by the 'last ripples' of the late Alpine tectonism in the Miocene. These folds were growing through the Late Cretaceous as plate tectonic forces were transmitted across the Platform of Europe along well established, long-lived Hercynian tectonic lines (Holder & Leveridge, 1986; Mortimore & Pomerol 1997). The Miocene event was the last of several tectonic phases and led to the over-steepening in the Tertiary of the northern limbs of Cretaceous periclines and to short-circuiting of gaps between *en echelon* Cretaceous periclines.

Perhaps the most remarkable outcome of the last few decades of work on the Chalk has been the demonstration that far from being a period of tectonic quiescence, with a simple sea-level rise leading to chalk blanketing Europe, the Late Cretaceous was a period of pulsed tectonic growth of faults and folds. This growth tectonics was driven by far-field stresses generated by plate motions, translated along strike-slip faults with dextral transpressional movements. The tectonic movements provided the topography upon which sea-level fluctuations acted, and in combination, tectonics and sea-levels produced lateral variations in thickness, sediment type and contemporaneous sedimentary structures (including slumping and fracturing). This re-interpretation of the Late Cretaceous has a large impact on the ways we model the Chalk for petroleum, hydrogeology and engineering.

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I am particularly indebted to Prof. Akiva Flexer of Tel Aviv University and his colleagues in the Geological Survey of Israel for wonderful fieldwork and discussions on the Upper Cretaceous of the Syrian Arc. Similarly, the late Prof. Gundolf Ernst and his research team, Frank Wiese and Marcus Wilmsen at the Frei University of Berlin introduced me to the Subhercynian Basins of Lower Saxony on many occassions and discussed the development of Subhercynian tectonism. My old friends Dr. Bernard Pomerol of Paris University, Dr. Haydon Bailey of Network Stratigraphic Limited and Christopher Wood helped on many field studies and with many discussions.

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Book review

The Cambrian Fossils of Chengjiang, China: the flowering of early animal life by Hou Xian-Guang, Richard J Aldridge, Jan Bergström, David J Siveter, Derek J Siveter & Fen Xiang-Hong, 2004, Blackwell, 233pp, £60 (hardback) ISBN 1405106735.

This is a beautifully produced book, full of colour photogaphs and reconstructions - essential when describing previously unknown forms of life.

The fossils come from a strata very near the base of the Cambrian, just above the famous Ediacaran fossils from Australia. Some are similar to their older relatives, but others are very different.

The text occupies the first 28 pages (6 chapters) and describes the sedimetation and preservation of the Chengjiang Lagerstätte. Many of the soft-bodied animals have left enough traces to establish their mode of life. The rest of the book describes each species in detail and covers the phyli: Algae, Porifera, Cnidaria, Ctenophora, Nematomorpha, Priapulida, Hyolitha, Lobopodia, Anomalocarididae (phylum uncertian), Arthropoda, Brachiopoda, Vetulicolia, Chordata and, as if that was not enough, they also list "Enigmatic animals"!

The account of each specimen is accompanied by clear photographs and, where possible, a reconstruction of the animal. A full description is also given.

These fossils from China have contributed greatly to our understanding or the evolutionary processes. At £60 this book is rather expensive, but is a must for those who research early life.

Jane Clarke BA Hons, BSc, MPhil (all Open)

The Building Stones of Dorset

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As the limits of the Heritage Coast extend to take in the red rocks of Sidmouth and Dawlish, I can name this greater Dorset as the source since Saxon times of three of the best building stones implicit in our built heritage if we value it. The three are Portland in its various forms; Purbeck in its several varieties, and finally, Beer Stone - the one less often referred to or valued. If this recognition generates a proper pride in John Chaffey and Doreen Smith of the Dorset Geologists' Association Group, they sadly have to accept that winning the same stones carries a current curse in the public inquiries and disputes which can erupt when countryside 'quality' seems at threat.

Everyone concerned with stone conservation in buildings, especially those deemed 'heritage' or 'listed', knows that the only sound and lasting repairs require a return to the original quarry source whenever possible. Substitutes of near-match stones, or what might be passed off as 'Portland-type' stone are seldom adequate in meeting the full requirements. Time and our testing climate quickly expose mistakes, or even deceptions, should they be committed.

Original quarries may have gone out of work, or even proved to have become exhausted of quality stone, but should be considered for re-opening. At this point planning authorities regionally are at present liable to be swayed by local opposition and say 'No'. Until recently it seemed almost impossible to change public opinion, but that may now be less immovable.

Two things recently may have opened up a chink in the previous defences: first, the amazing response to everyone's surprise to the TV series 'Restoration' presented by Griff Rhys Jones, saw millions of viewers voting by phone to save specific buildings which suggests a public sympathy for historic buildings and their conservation. As a follow-up second series is now well in hand, this seems an opportunity for us to add an element of geology.

The second breakthrough has to be admitted as 'jingoistic' to a degree. "No to French or foreign limestones!" said the tabloids as our growing dependence upon imported stone filtered through to the press. To some extent this heightened the scientific argument which we have advanced as being 'best policy' above, to the point where the DTI and the Deputy Prime Minister convened a steering group from industry and academia to look into reserves of key stones, and any problems which might hinder further exploitation. Eleven specific stones were selected for research. For the Heritage Coast and its three quality stones, Portland and Purbeck were investigated and figure in the Symonds Report published in April 2004. Aimed chiefly at planners and local authorities, its effect is yet to be seen, but a swing to a more understanding public might be achieved to our satisfaction. There has to be a role for active groups such as the Open University regional groups in making the wider awareness of the geological arguments.

Dorset stone in its natural context in the towns, villages and countryside is fully and excitingly covered in the book by Jo Thomas (1998), oddly identified with quarrying when the content is really buildings and their sourced stones. With this existing I am able to switch my remarks to Dorset stone as it is dispersed to all parts of the country (and overseas), with some comment upon qualities and interpretations.

For so small an area of the earth's crust, Britain is particularly well endowed with good building stone: limestones, sandstones, and granites. Focussing down more closely, Dorset as a geographical area, is better provided than any other county of a similar size. On any judgement it has the best of our limestones. Before that gives rise to any smug satisfaction, can we quickly add the consequence: that planning permissions for quarry extensions let alone new quarries give rise to the most heated objections and downright opposition. While everyone pays lip service to the beauty of local stone, winning it to maintain that heritage can prove difficult.

It must fall to geologists, including those alive to the subject through the adventure of the Open University, to explain the vagaries of outcrops and the uniqueness of our best stones, if only to persuade those who would instinctively object to workings close to their homes. Theirs could be a proper pride in the quality and respect we have for Dorset stone. They should appreciate that all are household names; such is their fame.

For Dorset, there are three main stones to describe, with other, lesser stones interspersed and figuring in village vernacular buildings. Prime position would go to Portland Stone from the uppermost Jurassic, followed by Purbeck Stone but a little younger in the matter of time. The third stone requires me to stretch Dorset into nearby Devon to be able to add Beer Stone to my list. A hard chalk, it may not be as familiar as a quality building stone as the other two, but it truly has importance for at least two of the southern cathedrals as we shall see. All share properties which are of prime importance for building stones. They have a thickness in their bed in the quarry which would aIlow them to be worked in cube dimension which in turn could be cut freely as load-bearing blocks, tooled into carved capitals, or sliced into convenient cladding slabs. All would qualify as *dimension stones*. Equally, all are largely limestones with textures free of strong bedding or textural grain so that they can be worked freely in any direction from the block. All are thus *freestones*, another mason's term often used in architectural accounts. When there is shell accumulation on bedding surfaces, the stone is rougher weathering and tough, the harder weathering shell debris creating what would be called *ragstone* in contrast to the more valued freestones. Ragstones, however, are valued as plinth stone or string courses taking the brunt of wind, rain and frost. There is a fourth and final valued stone, that would be used for pavings and kerbstones. These are the thinner-bedded limestones or sandstones , the *flagstones*, mainly from the Purbeck series currently enjoying a considerable popularity in new contracts.

Portland Stone

To put Portland building stone into a proper geological context you need to go to the tip of Portland Bill (Figure 1) and balance on the cliff top to take in the cliff profile to Lyme Bay. The undercliff is slightly hollowed out by the sea, corresponding to the outcrop of the Portland Sands, not material of building stone quality. The jutting out cliff allows you to pick out two main bed units of between 1.5 and 2m thick. These are by name the *Basebed* and the *Whitbed* as worked and marketed by the stone trade. Both units have strong natural breaks as bedding planes, easing the

Figure 1. Portland Bill: cliffs showing the building stone projecting above the Portland Sand outcrops.

working of the stone with the minimum of physical damage. The strong vertical jointing completing the means of simply prising the l.5m^3 blocks by crowbar without the need of explosives. The blocks today are still split using traditional methods of plug-and-feathers, although nowadays the initial hole will be driven with a power-drill rather than a hand-drill. Jurassic seabed sedimentation may have been subject to pauses allowing shell (mainly oysters) to concentrate towards the top of the bed units. As architects are seeking to get the fullest value from the freestone character of the stone, they can ask for "shell-free" stone, when traditional scalping with a stone pick will trim the full block to a maximum height of l.5m.

As a lithology, Portland Stone is an excellent subject for analysis which allows us to recreate the environment of the Jurassic seas. The shell fauna is rich in oysters and thick-shelled bivalves which would live in a relatively shallow shelf sea. What depths would be right for oysters? As today, they would shun waters which were liable to be flooded with mud or terrestrial debris. The same waters must have been bottom current-swept, as shells were often reduced to fragments which became the nuclei of lime-coated ooliths (Portland Stone is an oolite as 'text-book' as Bath Stone at its best). Shallow shelf seas, warm and rich in lime in solution, has to be the conclusion from the frequency of ramifying patterns of shrimp burrows at well-defined levels within the limestone units. Direct comparisons with callianassid shrimps, active in the Tropics, active at a few centimetres below the seabed, offer a clear identification for the trace fossils. Perhaps most telling, however, must be the occurrence of flat discs and layered nodules of calcareous algae, requiring full light penetration for their success. From all of this faunal and floral evidence, it is difficult to think of water depths greater than 10 to 15m for the Portland Stone sea late in the Jurassic.

History of Use

The earliest use of Portland Stone is still a matter of discussion. It always seemed probable that it should date back to Roman times, but this needs confirmation which could come from alert geologists of the OUGS. Archaeologists,who might have solved this question often seem to have been content to record "stone" in their excavations without further refinement. As an example of this failure one need only cite the record of the Mithraic temple in the heart of the City of London conducted by Dr Grimes of the Museum of London. It was the first of excavations to receive close attention from the press, and was given the opportunity of being reconstructed close to Queen Victoria Street when the new building was raised above its original position. The token walls can be accepted as having been of Kentish Ragstone, but the column bases of the body of the temple, now in white Portland Stone, cannot be confirmed as being the stones 'as they were found'. The otherwise comprehensive account fails us on that critical fact. *It is up to us to remind archaeologists of the imperative need to have precise stone identification* and, if necessary, the assistance of a geologist on site to sort out matters of provenance, recycling and matters such as community economy,

Portland Stone is definitely to be seen in the window surround in the Well Tower of 1245, part of the outer wall to the Tower of London close to Tower Bridge, the main masonry being Kentish Rag. Once again, here is a situation where anyone can usefully identify and record occurrence and our present uncertainties can be cleared up. Popular history always credits Sir Christopher Wren with the choice of Portland Stone for the rebuilding of the City churches after the Great Fire of 1666 for its earliest main use, but we need to credit his predecessor, Inigo Jones, for choosing the white limestone for the Queen's House at Greenwich, the Banqueting Hall in Whitehall (1619-25) and St Paul's Church, Covent Garden for demonstrating Portland quality. From 1669, however, as Surveyor General of the King's Work, Wren set about the quarrying on Portland Island (Figure 2) on the grand scale which we have come to recognise continuing into the present.

Figure 2. The working face of a stone quarry, including Purbeck overburden to the dimension stone; dusty and hazardous as a working quarry.

Blocks remain stockpiled in two of the quarries, bearing Wren's mason's mark as having passed a quality control inspection which was one of the secrets of his work. Extraction was followed by sled movement to the cliff edge, where the dressed blocks were transferred by simple cranes into shallow-draught coastal barges which could strand themselves at low water on the stone shelf below the cliff, floating off at high tide to sail to Swanage Bay and transfer into larger coastal sailing ships for transport to the Thames.

On the island, the parish church of St George Reforne of 1777 stands as testimony to Portland Stone quality. The finely cut wall blocks sit with knife-edge contact, their surface retaining the comb patterns of the mason tooling intended to remove all surface flakes prior to surface weathering. Wind and rain in clean sea air have only added a thin crust of lichens in the centuries of exposure. As much is true of the forest of gravestone slabs and grander tombs which carry the evidence of the shallow three-dimensional carving which the freestone invited from the monumental masons of the island. Visions of the Day of Judgement and graphic representations of shipwrecks, as well as inscriptions in the finest cursive lettering are details to be noted from a visit to this Grade II Listed Church.

Since Wren's days, Portland Stone has filled our city centres and continues to do so when the stone is simply a thin cladding to modern steel-framed tower blocks. Used against all alternatives for government and civic buildings in Queen Victoria's reign, the familiar white stone was taken all over the world as a symbol of the British Empire. More tonnes are to be found in Lutyens' New Delhi and Donegal Square, Belfast, than nationalist politicians care to see. Another universal dispersal of the white stone has to be its use in the war graves of the Imperial War Graves Commission, when the simplicity and the recognisable stone conveys a very direct message more telling than more ostentatious monuments.

"The stone rejected of the Builder" (Psalm 118)

Figure 3. Portland Roach.

In working the valued Base and Whitbed units, quarrying involved the removal of an increasing thickness of overburden of higher, younger Purbeck strata for which there was no immediate use in the early years. There was also a higher unit in the Portland stones which seemed inferior. It was a bed which was spectacularly rich in open cavities, spaces which once had been solid shells of bivalves or snails. Rough textured and somewhat crumbly, Portland Roach (Figure 3) was removed to get to the sought-after stone, and stacked with the Purbeck debris, back-filling the quarries as they developed. This waste status remained true until

Figure 4. Portland Roach, The Economist, St James's Street, London.

in 1960, when the architects, Smithson and Smithson used Roach as a surface cladding to the tower to house *The Economist* off St James's Street in Mayfair (Figure 4). It also figured in the new buildings for St Paul's Choir School at the east end of the cathedral on New Change. In effect, they were using the rough texture as a contrast to the ashlar treatment of the conventional Portland Stone, able to ignore the porosity of cavity-rich Roach by attending to the water proofing of the load-bearing wall behind the cladding.

Over the past forty years, the adoption of Roach has grown apace by other architects so that it is to be seen in ministry buildings along Tothill Street, Victoria, and in Heffers bookshop in Downing Street, Cambridge. Truly, "the stone rejected by the builders has become the headstone of the corner" (Psalm 118) with a vengeance, but with interesting consequences for our understanding of the facies. Clearly, the rich shell fauna has always been appreciated. This is the limestone facies which provides the hollow spirals of the 'Portland Screw' and those deep cavities which, when plugged with plasticine, allow us to cast positives of the bivalve *Trigonia* complete with nodular ornament. In the past year (2002 into 2003) Roach has been used in the redesigned Paternoster Square in the Precinct of St Paul's Cathedral in place of the dismal towers of the Holford post-war offices. Scanning the surfaces, however, while a proportion of the total retains Roach characteristics, much of the stone shows survival of full shell, blue-grey against the white background matrix. Clearly, shell leaching by aggressive groundwaters must have been responsible for the cavity-rich normal Roach. As total stone working has removed beds deeper and deeper below the original land surface, the Roach bed has suffered less and less leaching, that process relating to possible emergence as Portland marine conditions gave way to the lagoonal and ultimately, freshwater regimes of the Purbeck.

One final observation: Portland Stone of quality is a rock confined to the roughly 15km^2 of the Isle of Portland. When we move to the Dorset mainland, the quality falls away. The outcrops of equivalent age in Winspit and the cliffs above Chapman's Pool are

marred by nodules and strings of black chert which destroy the freestone quality and the economic dimension stone character of the stone. Still further inland, when the Portland beds re-emerge from beneath the Chalk at the Dorset-Wiltshire border, the limestone has become soft and speckled with grains of green glauconite. Chilmark Stone, virtually Portland Stone in stratigraphy, is a building stone in its own right, but not in the same league as Portland Base or Whitbed. Generally, these patchy geographical variations are just those which we find if we survey present-day seabeds for biological or lithological patterns. The Jurassic seabed was no different in those respects.

Purbeck Stone

When it comes to the Purbeck Beds, slightly younger than the more famous Portland Stone(s), most people will immediately think of the shell-rich dark-coloured limestone which is traditionally known as Purbeck Marble. Marble it is to the trade in that it can be polished to a high finish, will retain that polish, and has another essential character in that it has a 'figure'. On the last qualification criterion, the limestone is crowded with freshwater snails which create a pattern to the 'marble'. As the stone has never been altered by heat or pressure, it fails to meet the requirements which geologists would set before calling a limestone a marble. It remains a well-used quibble which we can introduce when non-geologists borrow our clothes.

Purbeck Marble, however, is only one of three stone types which we actively exploit from a very confined area of Dorset, the so-termed Isle of Purbeck behind Swanage and Corfe. All contribute to what might be regarded as one of the most geologically orientated regions in the British Isles, where everyone had some role or association with the quarrying and mason trade extending back several generations. The book *Purbeck Shop*, reprinted several times, proudly boasts of this. That boast will cover working of some of the best paving slab limestone (Figure 5) on the one hand, and one of the toughest and most long-lasting freestone limestones on the other. We see the Purbeck flagstone limestone when we look at the overburden which has to be removed on Portland to give access to the more valued Portland Stone beds. Almost regarded as unwanted waste, it could be that some economic use could be made of the beds, if only to feed the trade in made-up fireplace surrounds or garden centre stone chippings, if not patio stone. All of that use, quite lucrative in itself, seems to happen in Purbeck. Flags are best seen in the lines of small quarries which extend west-to-east from Worth Matravers, through Langton Matravers to the hills above Swanage. Relatively thin beds of about 50-80mm in thickness, perhaps separated by clay wayboards making working easier, these are freshwater limestones, that character clearly indicated by the shell fauna of bivalves related to modern unionid or pisidia, little changed by evolution over the intervening 140 million years.

As limestones they have much of the character of lithographic stone, dense and compact, with a brittle fracture. They are rich in mud and never crystalline. Wide-spaced joints make them a natural shape for paving with a minimum of trimming, which leaves their intrinsic strength intact. Their shell content can lend them a role as ornamental stone. The shells are abundant as is often the case with freshwater facies. Blue or even black in colour, the shells appear as prominent outlines, ring-form, upon the bedding surfaces. Rubbed smooth, they can create patterns which vie with those of the more popular 'Marble' with its snails. As often is the case, the quarrymen have given their own pet names to what they regard as different beds in the sequence. So we have the poetic names such as Spangle, Grub and Thornback, traceable laterally as possible stratigraphical units, but sadly, absent from most of our more formal charts of correlation. Probably the non-English speaking world of geology is grateful.

There is a long history of use for Purbeck flagstone facies. It figures in Roman villas and probably in mosaic tesserae. It also was fashionable paving in Georgian towns (Bath, Winchester (Figure 6) and London where it served as early kerbstones when used edge-on). It also was taken with the English into the Empire. In Jamaica, an island sadly lacking in good useable limestone, it turns up in the fabric of Fort Charles in Kingston Harbour. What survives a dramatic earthquake of what was Nelson's base for his

Figure 5. Purbeck pavings, Winchester Cathedral precinct.

Figure 6. Purbeck Limestones set edgeways as kerbstones, Winchester Cathedral precinct.

Caribbean pursuit of the French, is part-paved with shell-bearing Purbeck flags. More is to be found in the burial grounds as upright ledgers capped by the winged souls and hourglasses we might find in the churchyards of Dorchester or Weymouth. Clearly, most were roughed out by Dorset monumental masons. They are found also in the family burial grounds found attached to the inland estates, including Halse Hall, the family home of the geologist Henry de la Beche. Both Purbeck and Portland stones occur in the Trafalgar Cemetery on Gibraltar. To bring use up to date, Purbeck Grub is to be found in the landings and stairways of the new British Library on the Euston Road, a place which is a visual stone feast.

Figure 7. Purbeck freestone blocks, West Front, St Paul's Cathedral.

It remains to mention the least-often cited Purbeck, yet one of the variants which may have a future at present not considered. This has to be the Purbeck Freestones, Lower and Upper, which are the cliff-forming units from St Aldhelm's Head to Durlston Bay. In what is termed Middle Purbeck, the Lower Building Stone can reach a thickness of 10 to 12m, thick enough to be worked as economic building stone in the last century. Often, this stone and the younger Upper Freestone, were worked to produce substantial setts which were used in street paving in south coast towns and London. The stone is semi-crystalline but bruises rather than splinters under use. It is well seen in the paved area before the West Front of St Paul's Cathedral (Figure 7) where it was placed in the course of the reclamation of the old burial ground in the 1890s. Thicker units, neither the Lower Building Stone nor the Upper Freestone could be quarried on any great scale, simply because the quarries would be visible behind the cliff line close to the route of the South Coast Path, one of our more popular long-distance routes, extending from Minehead to Poole Harbour.

This brings me to a troublesome issue which dogs the future of quarrying in this country, and our custodianship of heritage in buildings. Already the importance of Purbeck Marble (the snail limestone) for our Gothic cathedrals has been mentioned. Hardly one of them lacks columns or tablets of this lustrous stone which was deliberately set in contrast to our pale oolites or Caen Stone from Normandy. Unfortunately, the marble was produced from lime muds which were also sulphide-rich. Most shells are pyrite-coated and susceptible to corruption in warm moist conditions such as we find in interiors. So, there is a constant need for replacement stone from almost a single working quarry. When that quarry bids for extension of the area of working to Planning, what elsewhere may be a matter of routine, has in the past become a contested issue fought by local residents. We have to accept that first reactions to a proposal for quarrying will always trigger an anti-feeling. In Purbeck, it always seems ironic, given the long history and tradition associated with stone-winning, so one can only assume that the anti-reaction must stem from 'incomers' unaware of local history. Those same objectors would probably be in the vanguard in campaigns to save a threatened heritage building, especially if it was one of the cathedrals hungry for stone for repairs funded by the Lottery. If the last comment is true, then it is up to all geologists to bring home the point that it is no use looking for Purbeck Marble on remote areas of Salisbury Plain or deeper Wiltshire. The only source has to be on the Isle of Purbeck - full stop. Stone is a variable product as we have seen in the search for good Portland on the mainland, so this is the choice we have to put before an objecting public to test their commitment to heritage and building conservation. As much was the outcome and advice of a working party set up by the Deputy Prime Minister in 2002, which reported in May 2004 (Thompson 2004).

Beer Stone

Our third important stone drawn from Dorset and the adjacent East Devon coast, is Beer Stone, one of the hard chalks which have been quarried from outcrop and followed underground in adit mines from Burwell in Cambridgeshire, through the Bedfordshire and Hertfordshre Chilterns as Tottenhoe Stone, to the Dorset Wessex outcrops, but especially at the coast of Lyme Bay at Beer. No one would rate them as competitive with Portland

Figure 8. West Front of Exeter Cathedral (Beer Stone).

or Purbeck stones except for interior use, where Beer is as good as any stone. Look at Exeter Cathedral (Figure 8) and its amazing fan vaulting as proof of this. Originally, the many niches of the West Front were filled with effigies which have suffered over the centuries to an extent that many have been replaced by copies in the French limestone, Lepine, a stone with near-equal quality as a stone easy to carve. Ironically, the new figures were given extra protection against the usual pigeon blight, being covered with a nylon mesh netting (Figure 9). Sadly, netting can never be held tight and without free movement. Nylon mesh blown by the wind,

Figure 9. Deeply weathered medieval figures in Beer Stone, niches on the West Front, Exeter Cathedral.

successfully rubbed off the nose tips and other prominences. Best intentions can fail when architects can be short on geological awareness, but admittedly, even Portland Stone would fail in similar circumstances.For practical demonstration of Beer Stone, you could do no better than to look at the restoration work being done at Winchester Cathedral at present. Originally, the stones used were the Tertiary freshwater limestone, Quarr Stone from the Isle of Wight, a stone used from Roman times along the south coast of Sussex and Hampshire, even as far as the White Tower of William's Tower of London, to the extent that the shallow quarries in the equivalent of the Bembridge Limestone were exhausted by the 14th century. Some Purbeck stone was used, certainly, the marble figures in the ruined cloister, but latterly, Beer has been used in the cathedral stone yard.

Close to Beer, many of the local churches of South Devon, show Beer Stone and the nearby Greensand from Salcombe in a mixed fabric which may even include iron-redbrown ferricretes derived from the Tertiary sands of Hardy's heathlands. Such a mixture provokes a sad stone interaction as the types mentioned contrast strongly in their porosities. They 'drink' to different extents and frost and winds wreak havoc. As such, these churches offer us case histories in bad practices and poor conservation. In this, Beer Stone seems to suffer most from the contrasts from the other stone types. So, in this we might say that not only does Dorset appear to have been well endowed with good building stones, but also that it offers us insights into good practice in building conservation. For this, we should be grateful.

Addendum
The Geology of Canford School

When I came to Canford School for the 32nd Open University Symposium in July, I had not done my homework on the school and its setting, having planned to concentrate upon Wimborne and its Minster church. Walking into the campus from the Canford Magna entrance and skirting the splendid cricket field, I was duly impressed by the mansion, pale buff overall as it was bathed in morning sunlight. Details of tall chimneys, pediments and the tall tower seemed vaguely familiar as what passed for a statement to the outside world from a successful industrialist in mid-Victorian times (centre page Plate 1).

The pale-coloured bricks matched what we see in south Hampshire and nearby Dorset, fired from Tertiary clays in kilns with controlled oxygen flow during the firing. Stone dressings seemed to be either a soft buff-coloured mid-Jurassic limestone akin to Tisbury Stone from the Wiltshire-Dorset border, or some Caen Stone, a more orange-toned stone which is dusty to the touch. Neither have a fossil content, although a belemnite guard stood out at an entrance to the long gallery (?Tisbury Stone). So much for the main school building, which, with its twin wings extending to part enclose the formal garden with the fountain, made up a ground plan essential for a Neo-Tudor mansion in the 19th century.

Quite unexpected in this setting was a much older core which could take us back to the 15th century at least. This is what is called John o'Gaunt's Kitchen, which had been added to the Wimborne Building Stones Walk by Jo Thomas who knew that this part of the school would usefully set up what we were to see in Wimborne Minster which had been my main focus. Kitchen it was indeed as we could see from the outside wall which was virtually a chimney breast tapering upwards into a substantial chimney stack supported by stepped buttresses (centre page Plate 1). Inside, this proved to be so, with a walk-in fireplace capable of roasting an ox. This and two other fireplaces would have been quite in place in an Edward-the-First border castle.

The heat generated when the fireplaces were in use seems to have been contained by using the local ferruginous cemented sands and gravels from the Tertiary heathlands close to Canford for the fire back clearly visible from outside. Technically these heathstones conform to the definition of ferricrete as given by Lamplugh in Geological Magazine at the same time as he introduced the terms calcrete and silcrete, both widely used subsequently (1902). A similar adoption of ferricrete seems still to happen while terms such as 'carstone', 'ironstone' or 'ironshot gravel' are spread through the accounts of buildings in any of our Tertiary or Quaternary basins and heathlands. Like calcrete and silcrete, ferricrete implies the soaking of sands and gravels by groundwaters rich in mineral matter in solution. Drying out creates a rock from unconsolidated and porous sediments, either sands or gravels. It is really identifying a process rather than just a lithology - a kind of iron pan we would recognise in soil profiles.

In stark contrast to these strongly coloured stones, the bulk of the stonework of the upper chimney wall is of white slabs of limestone laid horizontally in good coursing. Close examination showed that most slabs are crowded with close-packed bivalve shell, a distinctive feature of the flaggy lithologies of the Purbeck succession. A few of the white stones are pock-marked by round cavities, which are the casts of charophyte oogonia. This would identify pieces of Bembridge Limestone, a freshwater limestone from the Isle of Wight, associated with another shell limestone, Quarr Stone, widely used on the mainland in abbeys, town walls and harbour quays throughout medieval times.

There is a sequel to all this. One week later when on the roof of Westminster Hall and scanning the Victorian Palace of Westminster, the resemblances registered. Canford Mansion was built for the ironmaster Sir John Guest of Merthyr Tydfil by

Charles Barry, more or less at the time when he won the competition for the rebuilding of Parliament after the fire of 1842. The Canford great tower and porte-cochère could have been part of the complex alongside Big Ben. It all fits retrospectively. Buildings and building stones can be as satisfying to the mind as micropalaeontology.

References

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Book review

Exploring Space, Exploring Earth: New Understanding of the Earth from Space Research by Paul D. Lowman, Foreword by Neil Armstrong, 2002, Cambridge University Press, Cambridge, UK, 362pages, including Bibliographical references and Index. £80.00 (hardback) ISBN 0521661250; £29.99 (paperback) ISBN 0521890624.

Paul Lowman is a geologist who since 1959 has worked with the Goddard Space Flight Center and has been involved with space geodesy, remote sensing, lunar geology and satellite meteorology. His aim in this book is to convince Earth-bound geologists that we are at a critical turning point in our understanding of terrestrial geological and geophysical processes because of discoveries due to measurements made from Earth-orbiting satellites and the study of other bodies within the Solar System made possible by space exploration.

It is an ambitious undertaking, within the confines of one volume, to explain the techniques involved as well as to draw conclusions about the evolution of the Earth's crust, and indeed the whole Earth, from the earliest detectable rocks through the role of impact cratering to his conclusion that it is the presence of liquid water that keeps plate tectonics going. Inevitably therefore the discussion is occasionally truncated, though there are ample references to the literature, organised slightly confusingly chapter by chapter at the end. There is a brief glossary, perhaps too brief for a work that claims to be understandable by someone with no previous knowledge in the field. Numerous Figures in the text and 25 Plates support the argument.

The first chapters deal with the techniques that have allowed a greater understanding of the Earth from satellite measurements, remote sensing, sea-surface altimetry and from space geodesy, pointing to immediate practical and economic benefits, such as the discovery of hydrocarbon sources or mitigation of volcanic and earthquake hazards, and also better understanding of phenomena such as the shape of the Earth, its rotation, the topography of the ocean floor, and gravity fields. The chapter on orbital remote sensing and terrestrial and extraterrestrial magnetic fields leads to the elaboration of a theory of the evolution of continental crust. Comparisons with other silicate bodies in this and the next two chapters move the argument forward.

Knowledge of impact cratering and its role in the formation of continents and ocean basins has had a great boost from space research. Lowman believes that a great impact may have ruptured the Earth's early crust, others have caused mass extinctions and the only remedy against eventual extinction of our species may be to spread out – another thing made possible by space exploration.

Chapter 6, 'Comparative planetology and the origin of the continental crust', is the core of this book, Where he courts controversy is in the realm of plate tectonics, which he concedes is by now accepted as an explanation of the behaviour of oceanic crust, but in his view is inadequate as an explanation of the formation and evolution of continental crust.

What, finally, makes Earth unique is the abundant liquid water, its temperature maintained through feedback mechanisms, many of them caused by life, and whose cooling properties drive basaltic magmatism.

OU students of Earth Sciences will find this an interesting and stimulating read.

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Nordic Stone, Edited by Olavi Selonen and Veli Suominen, 2003, Unesco Publishing, 64pp, £16, (paperback) ISBN 9231038990.

This is a research report on stone resources in Norway, Sweden and Finland. The publication is in 7 Sections, Section 1 being a brief introduction and Section 2 dealing with definitions and terms: geological terms do not always equate with names used in the stone industry, eg gabbros, diorites and diabases are referred to as 'black granite'. An informative table lists the materials quarried with a brief description of the stone and in which country it is produced.

Section 3 deals with Requisites for natural stone and covers geological, technical, economic and infrastructural criteria.

Section 4 - History and heritage – covers the 1,000 year history of the use of stone in architecture. There are several photographs illustrating the use of different materials including the amazing use of soapstone for the Gothic cathedral in Trondheim. I was interested to learn that although soapstone is a very soft rock it is apparently remarkably resistant to weathering in the hard Norwegian climate and many medieval soapstone buildings are still in excellent condition.

In Section 5 Stone resources and distribution are described for each of the three countries: the location, commercial names and geology are detailed for each stone.

Section 6 describes the technologies used in exploration, extraction and processing. This section is well illustrated, including a map of a ground magnetic survey of a soapstone deposit in Norway, showing that soapstone has a significant magnetic anomaly.

The final section deals with the sensitive issue of Environmental impact of the natural stone industry. One of the photographs shows an abandoned quarry in southern Norway which is used as an outdoor theatre.

At the end of the report there is a table showing Properties of selected types of stone, ie density, water absorption, compressive strength and flexural strength. A second table shows the quartz and biotite contents of selected granites, important to structural geologists because stone with a high quartz content is hard to cut and a high biotite content stone is more prone to wear. 18 varieties of stone are illustrated on one page, including the well-known Balmoral Red granite and Blue Pearl Larvikite. There is an Index of locations and commercial names. Most of the References and Further Reading relate to Scandinavian publications.

I found this publication extremely interesting and informative: it is very well illustrated and easy to read. My only criticism is that some of the information had been previously published in local languages and there are one or two words which have a rather strange translation.

The publication can be obtained in England from The Stationery Office Books, Publications Centre, 51 Nine Elms Lane, London SW8 5DR, e-mail: book.enquiries@tso.co.uk; or on line at http://www.tso.co.uk/bookshop

Elizabeth Maddocks BA (Open)

The discovery of the Wytch Farm Oilfield, Dorset

Vic Colter, former Chief Geologist, British Gas Corporation

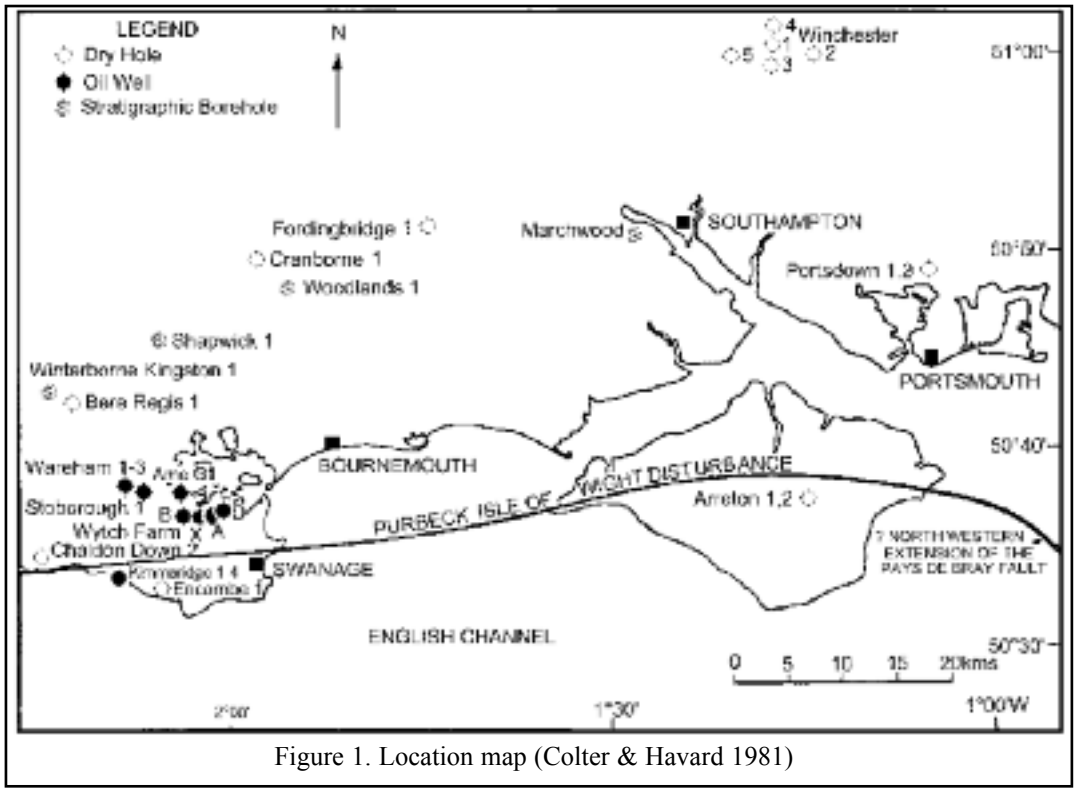

Figure 1. Location map (Colter & Havard 1981)

Introduction

I first got involved in exploration in Dorset in 1968 after leaving Shell and joining a nationalised body called the Gas Council, later to become British Gas Corporation. When I joined, the government had just been re-organising all its on-shore licensing regulations and had just issued two sets of licences to a group operated by BP, including the wholly owned subsidiary Gas Council (Exploration) Ltd (GC(E)) as a non-operator. BP had negotiated a work obligation consisting of one deep well and six stratigraphic holes which were meant to go to the top of the Jurassic and find out if there was the possibility of there being Wealden pinch-outs; they were also to map the Jurassic subcrop.

I never saw what the point of this was. Having spent some time in Canada in the Plains where there is immensely close well control, I realised that the six holes in this area would tell you nothing – even if you knew what you were looking for. Two wells at Shapwick and Woodlands were drilled (Figure 1) but I suggested that, instead of drilling the remaining four shallow holes, we offer the government an alternative of drilling one deep exploratory well. This would be cheaper and, if properly located, would yield a lot more data. BP agreed to this. This second well could be thought of as the Wytch Farm discovery well.

At the time, there were two wells in the basin which had found oil: the first was Kimmeridge No.1 which was covered by a BP Mining Licence. Our partners scrupulously kept all the information to themselves, so we did not know much about it, beyond the fact that it produced from the Cornbrash and had produced far more oil than the envisaged structure would allow. I imagine BP's secrecy was because it was on the coast, and they thought there was the possibility of some hidden bonanza offshore, where we were not partners.

The other well was Wareham No.1 which had tested oil from what was said to be the Inferior Oolite. It was never properly production tested and it was shut down and suspended. Round about 1970 Peter Hinde, head of the Exploration Department at Gas Council, suggested that a pump test be conducted to see what it would produce, but BP were reluctant because if it was a bad test it would downgrade the whole basin. What they really thought about the whole basin will emerge shortly. The well was, however finally put on pump and produced at about 100 barrels of oil per day, with some water. Since it was drilled on a single line of what Peter Thompsett, our Chief Geophysicist called "stone-age seismic", its chances of being on the crest of the structure were very slight, and as water-cut increased, it was shut in to conserve energy in any updip structure. (Post Wytch Farm and more seismic Wareham No.3 was successfully drilled on the crest.)

In 1971, BP's Work Programme and Budget for 1972 noted that "the area shows a marked lack of good reservoirs". This view depended on the fact that the two producing wells in the area each produced from different thin, fractured limestones, and there seemed to be no way of predicting this type of porosity. The Bridport Sands had been logged as siltstone in Wareham No.1, except for a few feet of sand at the top.

The 1972 Work Programme and Budget called for the drilling of two wells. The first of these was drilled at Cranborne (Figure 1) and was dry and abandoned after penetrating the Triassic Sherwood Sandstone.

Gas Council's Operatorship

From 1967 until 1972, Peter Hinde had been taking on staff to monitor the operations of our partners, but ultimately with an operating role for Gas Council in mind. It is fair to say that Peter laid the foundations of the successful Exploration and Production Department of GC (later British Gas Corporation), subsequently to emerge as the privatised world-wide BG Group plc, based in Reading. Peter's vital contribution went completely unrecognised. His first foray into operatorship had been well-site work for our partners, Home Oil, in Yorkshire. He then approached BP with a view to splitting the UK onshore into two, with BP operating one half and GC the other. BP agreed, and the country was split more or less north-south. BP preferred the apparent certainty of the Zechstein gas in Yorkshire and the Carboniferous oil in the East Midlands, over Dorset with its "lack of good reservoirs". Peter gladly took the half with Dorset, with the thought that it was

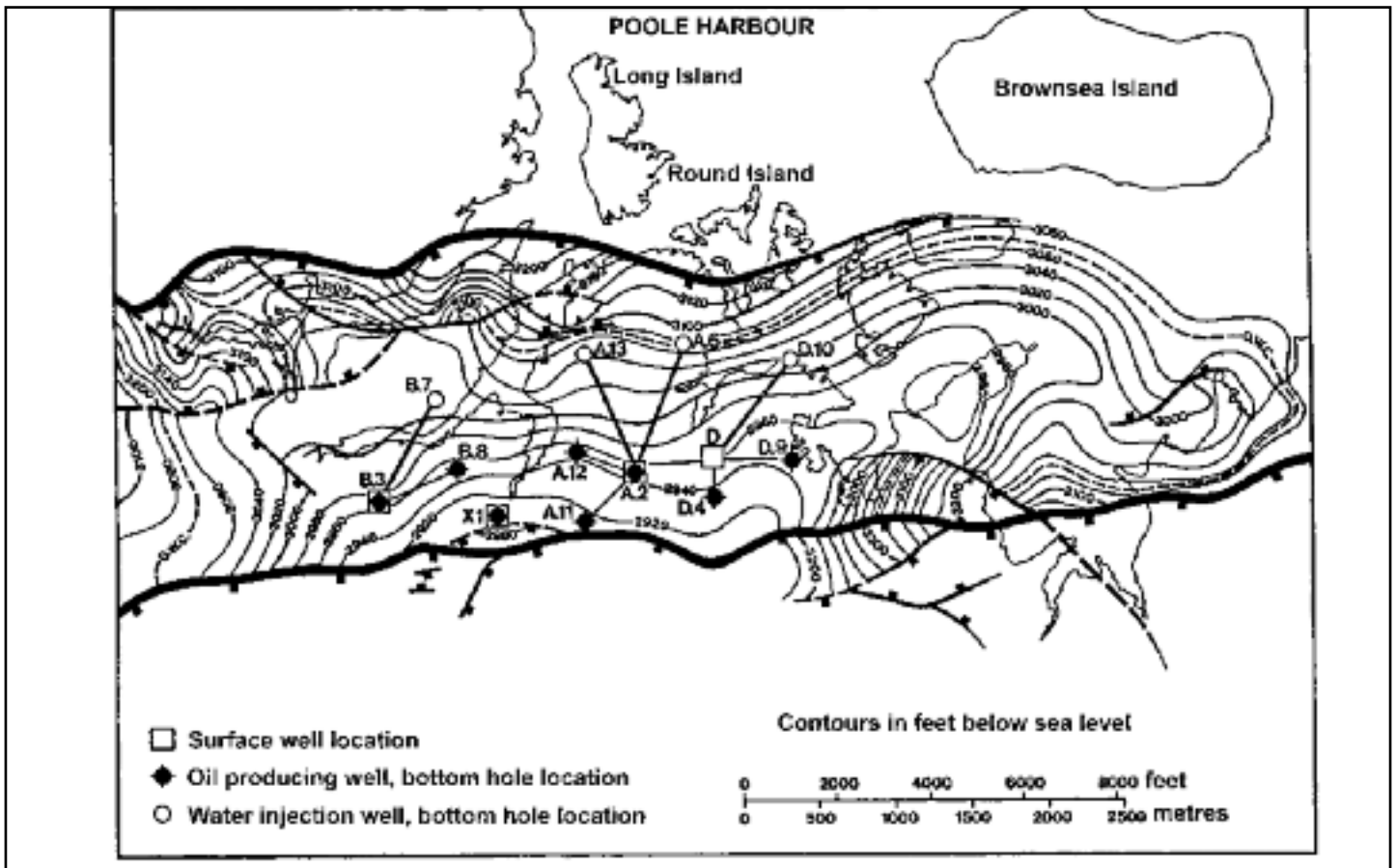

Figure 2. The Wytch Farm Olfield - contours on the Jurassic reservoir and development well locations (Hinde 1980).

a cheap way of looking at prospects in the Channel, where we were exploring with a different group. The change-over took place in July 1972.

As July 1 1972 approached, it suddenly occurred to me that if we were taking over the operatorship, we ought to have our own views about what was going on in the Jurassic. From my recent experience in Alberta, I decided to lay out some litholog and well-log-based correlations on a vertical scale of 1:5000. This scale produced immediate problems, in view of the disparate scales and presentations of the old wells. Drawing Office came up trumps, however. One section started in the Weald Basin and ended at Wareham No1. One day I glanced over the shoulder of a young lady colouring in the lithologies and asked her why she had not coloured in all the sand in part of the Wareham section, the Bridport as it turned out. I could not, at 1:5000, see the lithological symbols, but could see the micro-log. She flourished the full-scale log and said, "It's not sand, it's silt." I then realized what had been staring everyone in the face for years, namely that there was a fundamental contradiction between the lithology as logged and the micro-log (and others, it turned out), and that the Bridport section was almost all sandstone, with thin tight bands.

A micro-log is an old style of log which was discontinued in the North Sea until it was brought back by popular request. Imagine that the well bore is full of drilling mud, which has multiple functions, one of which is to keep the hydrostatic pressure in the section penetrated under control. The mud column in the well will slightly overcompensate and if a permeable formation is encountered the mud will tend to infiltrate into the permeable formation, leaving a mudcake on the inside of the hole. This can be seen on a caliper log. The micro-log is an electrical resistivity tool with a very shallow penetration. It measures two resistivities, one is that of the formation invaded by mud filtrate and the other is the resistivity of the mudcake itself.

Wherever there is separation between the two curves, there is a mudcake buildup, so the log is a qualitative indicator of the presence of permeability. The Wareham log looked exactly like the cliff outcrops of the Bridport Sands, with the cemented bands represented by high electrical resistivity peaks, and the permeable bulk of the section by micro-log separation. I thought that this was the "missing" reservoir rock in the basin. A review of drill stem tests on other wells that had only recovered water confirmed this view. It also occurred to me to look at the perforations in the casing through which Wareham No.1 was producing. It turned out that some of them were in the top of the Bridport Sands. It seemed likely that some, at least, of the oil was really coming from the top of the Bridport Sands and not the supposedly fractured Inferior Oolite. It was obvious that we needed to look for a bigger structure, where there was the chance of a bigger column of oil than we were finding at Wareham. This revised view of the prospectivity of the basin was duly conveyed to our partner, as the first act of our operatorship.

Wytch Farm structure

Our seismologists had been working on data shot using BP's in-house, rapidly aging, seismic equipment. They had mapped a structure at a place called Wytch Farm (Figure 1). BP's seismologists had also mapped this structure. We took over the operatorship on 1 July 1972 and there were two wells in the budget that year. BP had drilled one at Cranborne and we immediately recommended the other one

be drilled at Wytch Farm (Figure 1, X). This was turned down flat because the second well was meant in BP's mind to be a follow-up to Cranborne, but since Cranborne was a dry hole there was to be no second well.

The structure at Wytch Farm is bounded to the south by an E-W fault, which does not penetrate the overlying Cretaceous section, and relates to the Kimmerian earth movements controlling many of the North Sea Jurassic discoveries of the 1970s. The Cretaceous beds overlie the Oxford Clay unconformably. The fault hades to the south at about 30°. The reflector initially used to map this structure was the Cornbrash, but as time went on, better techniques allowed the direct mapping of the Bridport Sands. Figure 2 is a structure map, published by Peter Hinde in 1980, on the Bridport Sands, duly approved by BP's engineers and showing the eventual four surface sites and the deviated producing and water injection wells. Interestingly enough, at the same time we were refused permission by BP's explorationists to show any structural contours on the Bridport Sands (Colter & Havard 1981 fig 2)

The Wytch Farm No.1 discovery well

In the fullness of time in 1973 there came an obligatory surrender of half of each licence. BP surrendered absolutely everything except 50% of the one on which they had eventually agreed we would drill the Wytch Farm well. BP agreed to drill the well in 1973, provided it was a cheap well and would only go as far as the top of the Bridport Sands. I said that was nonsense because their man had not seen the Bridport Sands in Wareham No.1 previously. So I recommended that we drill down to a clear limestone marker in the Lias, which in the event turned out to be very important, because the situation I had envisaged had actually happened. We were not allowed to use a mudlogging unit on the well to save costs. The mudlogging unit depends on the fact that as the drill goes through a hydrocarbon-bearing formation, the mud and cuttings bring hydrocarbons to the surface and these can be detected by chromatography and various other methods. There are companies who specialise in logging these occurrences. BP did not want to incur the costs of a mudlogging unit, so I said we should at least get the simplest sort of gas detector and let the well-site geologists use it. They agreed and we started drilling the well late in 1973. Unfortunately, we had to put an inexperienced geologist on that well for other operational reasons, and the first thing that happened was that there was a power cut, so he was looking at the cuttings with a hand torch. Then there was a sudden cold snap and the rig was cut off by snow and his hose pipe which was used for washing the specimens froze. Eventually he ran into the Lias limestone marker, high to prognosis, not having recognised the Bridport Sands. So he went back and looked through the cuttings and found the Bridport Sands and discovered that they were oil-bearing. The gas detector had failed to detect the oil as the pipe fetching the air from the mudstream was kinked against the wall! The seismologists later went back to their records and saw a previously unrecognised small fault on the lowest marker, the Cornbrash. The well had gone into the upthrown block of the fault; so the Bridport Sands were higher than we thought (Figure 2, well X1). It was a vindication of the policy of drilling to a marker that could not be missed.

We ran a suite of electric and other logs and John Baines, the well log analyst, interpreted the logs to his satisfaction, interpreting them to be oil-bearing, but BP sent a team consisting of their chief analyst and his two minions. The minions were sent down to the well in the middle of the night while the analyst went to bed. The BP representatives thought the well was water-bearing, so they all trooped down to the hotel and consulted the chief analyst who confirmed that in his opinion the Bridport was water-bearing. In the meantime, John Baines had ordered the logging team to take side wall cores. This tool lowers a series of short hollow steel cylinders into the hole on a wire-line. These cylinders are explosively fired into the formation at predetermined depths, in the expectation that some of the formation and its formation fluids will be retrieved when the whole device is pulled to the surface. By the time John returned to the site they had retrieved the side wall cores, which were found to be oil-bearing. The chief still insisted it would go to water but the last I heard it still had not after 20 years. The whole thing could have come to a grinding halt and we could have abandoned the well if we had agreed with the BP interpretation. The well was tested and oil flowed to surface.

As soon as Wytch Farm No.1 discovered oil, BP came scurrying back with a recommendation to re-apply for the licences that we both had surrendered. We kept the bits we had hung onto, but which BP surrendered.

Development of the Bridport Sands discovery

In 1974 we set about developing the oil field and somehow the information got out and hit the Press. Immediately, everyone was up in arms. There seemed to be a general belief that exploring for and developing oil was a danger to everything on the face of the earth. This is a very good example of how things can backfire, because at that time the oil industry was starting to develop oil fields in the North Sea and companies were proudly showing pictures of the seabed platforms they were going to erect, next to Nelson's Column, the PO Tower etc. The people of Dorset thought that these were going to be erected onshore all over Dorset. There was concern about an orchid that owed its presence to changed pH of the soil of the road verges, as a result of introduced limestone ballast. There was also concern for a spider that only lived in abandoned quarries, as well as for the measurement of ruts made by vehicles to see whether a particular type of beetle could get up and down. The local "ball clay" people worried about compensation for sterilisation of clay, with exclusion zones around wells. They suggested that the oil company drill all over the area to map the distribution of clay and to see where any exclusion zones might contain exploitable clay because they could not decide that for themselves! Peter Thompsett , our Chief Geophysicist, had noticed that the parent company had just acquired a British seismic company to whom we were about to offer a huge contract for seismic in the Irish Sea; as soon as this was mentioned these problems evaporated. Another environmental factor was that the railway might be used to get the oil to the refinery, and interfere with steam enthusiasts' activities.

A requirement of the approval to develop the field was that all development and water injection wells should be deviated from four surface sites.

Events leading to the Triassic discovery

In the meantime, there was a drilling obligation on the licences to the east, which Gas Council had retained, and we decided on drilling Arreton No.2, since Arreton No.1 stopped before it got to the Bridport Sands (Figure 1). We were very well aware that the Bridport Sands might well have disappeared so far to the east. We drilled Arreton No.2 and there were no Bridport Sands. We drilled

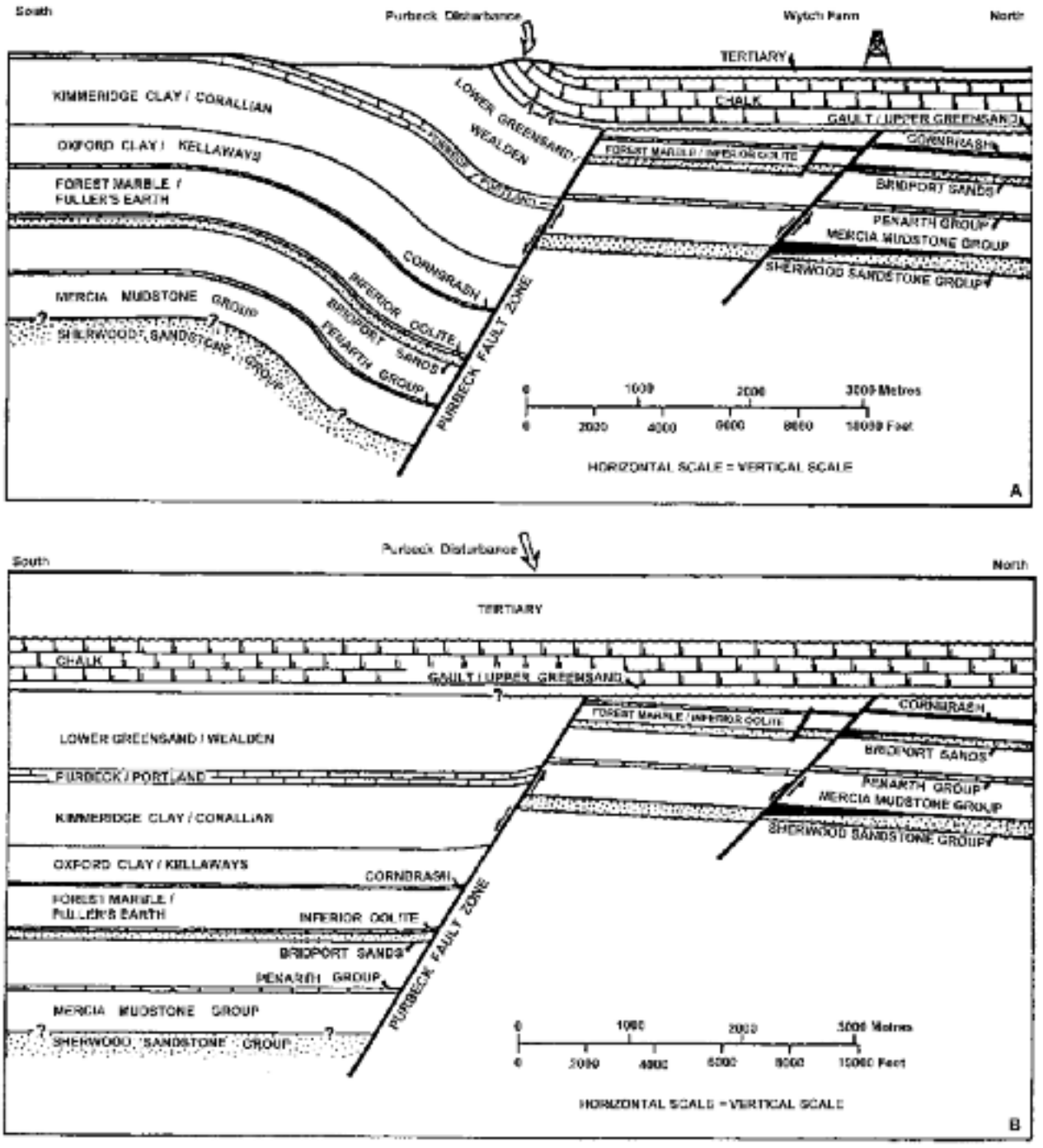

Figure 3. Interpreted structural sections through Wytch Farm Field and Purbeck Disturbance.
A) Present day;B) Tertiary, before Alpine Earth Movements (Colter & Havard 1981 fig 3).

on through an awful lot of red beds before we decided we had gone from NRS to ORS. How we picked the boundary escapes me after 30 years. A thick Wealden and complete Jurassic section were penetrated.

During this time, BP had done some organic geochemistry at Sunbury, and they had found that the organic material in the samples from Wytch Farm was immature. This concept of maturity depends on the observation that organic material in sediments changes with exposure to increasing temperature, as a result of increased depth of burial. The changes from peat to anthracite are an example of this. This maturity can be indirectly estimated by observations on increased vitrinite reflectivity (the black, shiny stuff in coal) and increased darkening in spores and pollen. In the case of oil source rocks, at low temperatures biogenic methane gas (marsh gas) is given off, but with increased temperature, oil is increasingly evolved, until at the highest temperatures the volatiles in the organic material are cracked to methane gas. The Wytch Farm oil was mature medium to light oil, but paradoxically, the sediments were immature. BP also did some work on the oil. This dealt with $^{13}C/^{12}C$ ratios in parts per ml relative to the Peedee belemnite. The Peedee belemnite is a belemnite from the Peedee formation somewhere in America, which is taken as the standard; the more negative this figure, the less ^{13}C is present, and a distinction between marine and non-marine material appears.

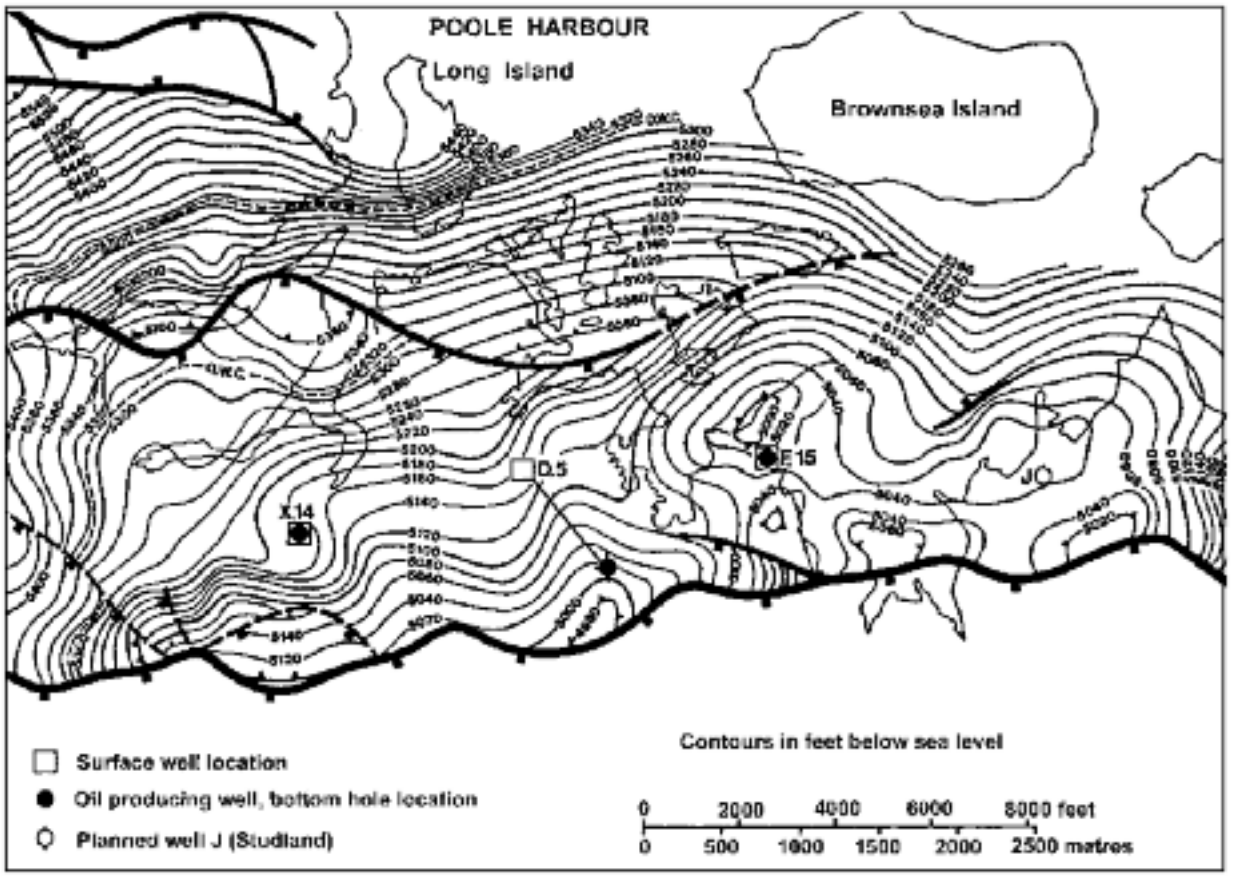

Figure 4. The Wytch Farm Triassic structure and relevant wellsites (Hinde1980).

Land plants and hence coal, are systematically more negative than marine plants, because there is less ^{13}C in atmospheric air than in dissolved air. BP saw this and they announced that the crude oil in Wytch Farm, being about -30 parts per ml on this scale, was of non-marine origin. This somehow got turned into a non-marine source rock. No-one could think of one, but Bruce Selwood from Reading told me that he had met BP geologists who had said confidentially that the oil source rock for Wytch Farm was Devonian. These geochemical data all seemed somewhat puzzling, but we had an oil field to develop, as well as a very large gas field in the Irish Sea (Morecambe), plus our non-operated activities, including the fourth round of North Sea licencing.

At some point, our North Sea and Channel partners Amoco had paid a "bottom-hole contribution" for access to Arreton No.2 data and samples. We also threw in a sample of the Wytch Farm oil.

One day in the middle of 1976 I got a call from John Fuller of Amoco who told me, off the record, that their Tulsa lab had found rich source rocks in the Lias and Kimmeridgian in Arreton No.2 well, and that these source rocks were at or about peak maturity. They also considered the Wytch Farm oil to be a normal Jurassic marine oil.

I thought about the apparent lack of source rocks in Wytch Farm section, and it was obvious immediately that the Kimmeridgian was cut out by the Cretaceous unconformity, and that we had not drilled the complete Liassic section. Strangely, also, BP's sampling of the Liassic rocks was erratic and seemed to concentrate on the Bridport Sands, the reservoir not the source!

I then started looking at the question of the freshwater source rock and did a bit of reading. Non-marine plants may have the right sort of isotopic composition, but non-marine plants do not have to be deposited in a non-marine sediment. I had read that a large part of the Gulf of Mexico is dominated by Mississippi land plant material, so these organics did not have to have been deposited in a non-marine sediment. Amoco said that the Wytch Farm oil was a normal Jurassic marine oil, so I concluded that it may have a land plant isotopic signature, with the organic material deposited in a marine sediment. There was, however, still the anomaly of the lack of maturity in Wytch Farm, on the downthrown, or apparently deeper, side of the Purbeck-Isle of Wight Disturbance (Figure 1), versus the reported maturity of the same section in Arreton No.2, on the upthrown, or apparently shallower, side.

I pulled out a cross section drawn earlier by the late Dr Ken Barr, through Wytch Farm and the Isle of Purbeck (Figure 3A). Wondering what would appear if the Tertiary inversion were removed, I took a pair of proportional dividers and a pencil and redrew Ken's section on a smaller scale, flattening it on the Base Cretaceous (Figure 3B). I imagine that computers do this sort of thing nowadays. It was immediately clear that, as a result of the presence of about a couple of thousand metres of younger Jurassic and Wealden sediments to the south, the likely source rocks in the Jurassic Kimmeridgian or Lias had been buried to quite adequate depths for oil to have been generated, before the inversion (Figure 3B). This oil could then easily have migrated into the Bridport Sands to the north. The realization then dawned that in so doing, the oil would have to have passed the thicker, more porous, Triassic Sherwood Sandstone. In a report summarising this study I wrote that, "consideration should be given to taking a well down" to test this theory. You might think this sounds a bit mealy-mouthed and not a very strong recommendation, but I knew perfectly well what the reaction was going to be.

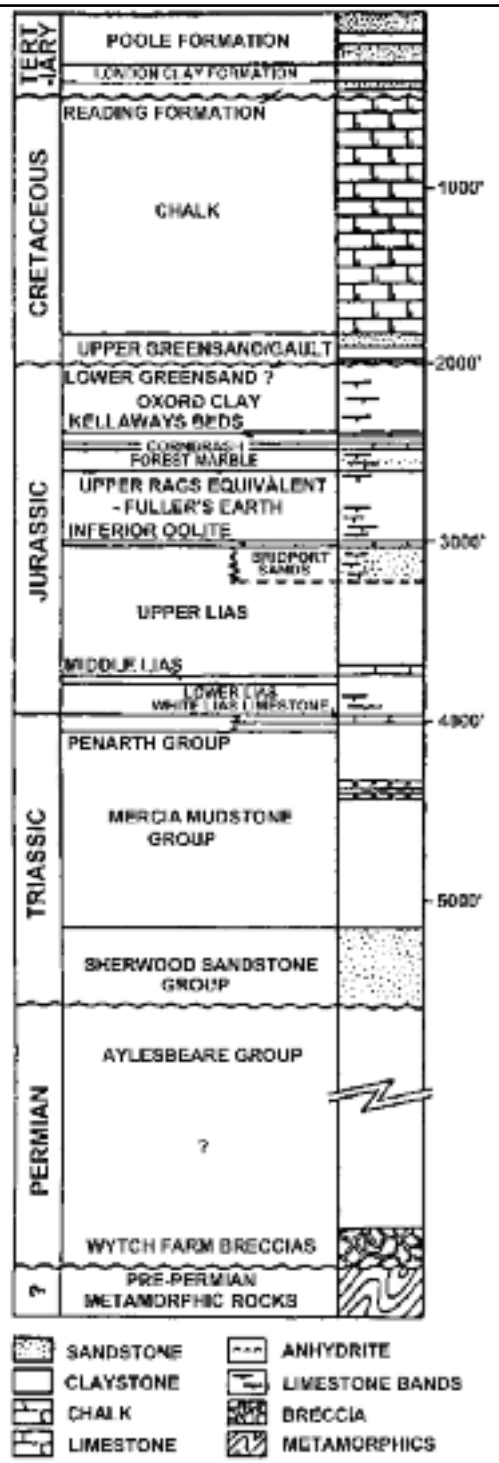

Figure 5. Stratigraphic column, Wytch Farm Field (Colter & Havard 1981).

The Wytch Farm D5 Triassic discovery

The next year (1977) we recommended a well to do just that. The first reaction was from our own general manager, who had been brought in from the private sector to show us how to do things (which he did to his own great satisfaction). The first thing he said was "What's all this about oil in the Trias – who says there's oil in the Trias? Colter? What does Colter know about it?!" "It's in his report," "What report?" So I was called to his room and he told me that if I could find the report he would be glad to look at it. So I found it in the middle of a big pile of reports. He read it and agreed we should drill the well.

I had sent an expurgated version to BP because I could not give them the Arreton information, much less Amoco's bootleg geochemistry, and got no reaction from them until we recommended this well. To be fair, the people in East Midlands were quite favourably disposed to it, but some of the people in London were not. I will never forget one chap: his face went red and his moustache bristled and he said it was absolute nonsense to suggest there could possibly be oil in the Trias at Wytch Farm, because there is no oil in the Trias at Cranborne and no oil in the Trias at Wareham. The answer to this was that no Wareham well was drilled on the crest (incidentally, there is no oil in the Trias at Wareham No.3 eventually drilled on the crest). At Cranborne there is none because (a) it is a long way from the postulated source and (b) it is a Tertiary structure so it was formed after the postulated time of migration. They suggested that we should test the theory on the next wildcat well, but I argued that Wytch Farm was the place we knew to be on the oil migration path, so that was where to test. As Jack Burst of the Shell Lab in Houston used to say, "If you wants to shoot ducks, you goes where ducks is." BP were not keen on this approach, because we were in the middle of the Bridport Sands development drilling programme, and a well to test the crest of the structure at Sherwood Sandstone level presented mechanical and other problems. The cross section in Figure 3 shows that, as a result of the approximately 30° hade of the fault, the crest at lower horizons than the Bridport Sands lies progressively further south, with increased depth. In order to reach the Sherwood Sandstone crest, it would be necessary to drill a deviated well from the surface location (Figures 2 & 4, D), building up the angle of deviation slowly. As a result of this, if the well were to be dry in the Trias, then it would have been too close to the vertical well from the same site at Bridport Sands level to be a usable producing well. The two wells would have interfered with each other.

Eventually, however, it was agreed to drill what was effectively a wildcat well to the Trias (Figure 4, D5). This well was drilled at the end of 1976 and penetrated an oil column of about 300 feet.

The news got out in the same way as that of the earlier Bridport Sands discovery, as a result of indiscretions.

In the paper read in 1980 and published in 1981, we were refused permission by BP's Exploration Department, to publish any map of the structure at Triassic sandstone level, but at the same time BP's engineers gave Peter Hinde permission to publish the map shown in Figure 4 of this paper.

Subsequent to the drawing of the map in Figure 4 a chance occurrence proved the presence of the oil in the northern fault block, which had only previously been inferred to be present. A deviated well was being drilled to tap the mapped structurally low area north of the F surface location under Poole Harbour. The location of the dotted fault in this area was somewhat conjectural, as seismic control in the shallow water was poor. In the event, one Sunday afternoon, the well suddenly went from Triassic Mercia Mudstones into the Sherwood Sandstone, which was high and oil-bearing. The fault proved to pass much further to the south than had been mapped, and the proven reserves of the field became bigger. The Wytch Farm Field became the largest onshore field in a large part of Europe and, I believe, a "giant" in the American classification.

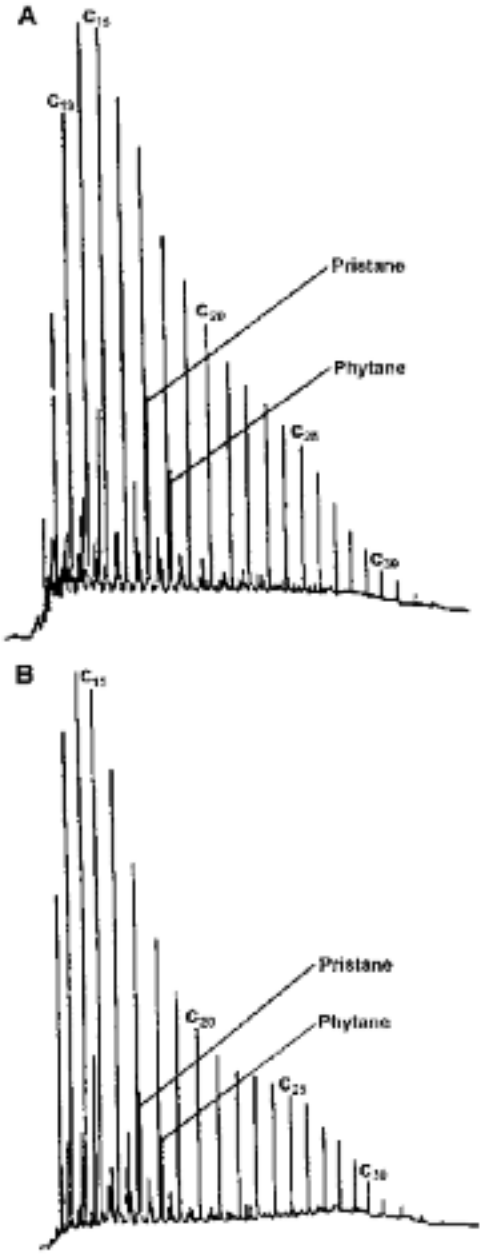

Figure 6. Chromatograms for C_{15+} paraffin-naphthene fractions, Wytch Farm Oils. A) Bridport Sands; B) Sherwood Sandstone. (Analyses by Geochem Laboratories UK Ltd. Colter & Havard 1981)

Cores taken in the Sherwood Sandstone showed that, as at outcrop, this formation seems to consist of fining upwards, braided stream channel fills. One can speculate about the lateral drainage of oil and water-drive through such a complex of more and less permeable rocks, but by now BP must have plenty of actual production data.

Figure 5 shows the stratigraphy of the Wytch Farm Field as penetrated in the D5 Triassic discovery well. At the time of publication (Colter & Havard 1981) the lowest usable seismic reflector was the Penarth Group, and the lowest reservoir the Triassic Sherwood Sandstone Group. The Aylesbeare Group sediments were drilled using a turbine drill and a diamond bit. As a consequence the cuttings were very poor. A core taken at some point showed the presence of shale or slate conglomerates. We were not allowed to show the thickness of this non-productive section in our 1981 paper for some reason, but one can get a good idea by reading the text (Colter & Havard 1981 p501).

The D5 discovery well bottomed in some greenish looking phyllites for which Fitch and Miller in Cambridge came up with a likely date of Middle to Late Devonian age.

Oil characteristics

The chromatograms from the oils from the two horizons are very similar. They both trail off into quite high molecular weight, waxy hydrocarbons probably the product of the land plant material mentioned above, but the two oils are essentially from the same source (Figure 6).

Subsequent events

The chronological sequence of events during GC(E)'s involvement in the Wytch Farm Field is as follows:

1968 - The production licence granted to the group

1972 – Gas Council (Exploration) Ltd. [GC(E)] becomes operator

1974 - Oil discovered at Bridport level at X site (Figure 2)

1975 - Extent of field proven at Bridport level at A, B and D sites

1977 - Triassic oil reservoir discovered D site (Figure 4).

1979 - Production begins March 1979

1980 – Full production established

1980 - Margaret Thatcher decides to privatise GC(E)'s share of Wytch Farm and give operatorship back to BP

Early 1980s – GC(E)'s 50% was sold off to half a dozen or so smallish companies, who must have done very well out of it since.

One could be forgiven for feeling that the reaction was "thanks very much for finding it, now buzz off". However, as the former chief geologist of BP subsequently said to me, "With all due respect to you, Vic, if you had not found Wytch Farm, somebody else would have done". I felt like grabbing him by the lapels and saying, "Well, I know who it wouldn't have been".

There is one last anecdote about how I felt Wytch Farm might have been saved from privatisation. In 1981 the union NALGO decided they were going to call a one-day strike because the Tory government was threatening to privatise the gas showrooms. Peter Thompsett and I had been members of the union and benefited from the fantastic salary negotiations they conducted on our behalf, so we thought we ought to show some solidarity and not just take a day's holiday as some people did. So we went on strike for the first and only time in our lives, and a couple of weeks later I was called before the new general manager, fresh from Southern Gas in Southampton. I was standing on the mat like a defaulter before the CO, and he said that he was very disappointed by my behaviour, "This is not expected from the Management Team". So I explained that I was not striking for personal gain but to defend the sacred gas showrooms of the industry for which I worked, which I had only visited twice in my life. This cut little ice. The gas showrooms did not get privatised, which showed how effective our strike was, but Wytch Farm did, and I think if we had gone on strike for Wytch Farm it might not have been privatised either.

Acknowledgements

The author wishes to acknowledge the contributions made by those staff of GC(E), mentioned and unmentioned in the text, in geophysics, reservoir engineering, drilling, environmental planning and development engineering to the bringing to fruition of the geological models proposed in the early and mid 1970s.

He also gratefully acknowledges the efforts and patience of Jane Clarke in providing OHP material for the talk and in drafting of the text of this paper, initially from the recording of the talk, transcribed by Jenny Parry.

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Book reviews

The Cretaceous World by Peter W Skelton, Robert A Spicer, Simon P Kelley, Iain Gilmour, 2002/2003 Cambridge University Press, 360pp, £27.95 (paperback) ISBN 0521538432.

This book is the textbook for the Open University course S369, 'The Geological Record of Environmental Change'. There are thirteen chapters written by different authors, but the style is the same throughout. It is easy to read, though it is definitely a textbook. The authors have used the first person 'we' so that it reads like a person giving a lecture. There are questions and answers in the text, rather like an OU unit. Yellowish background boxes contain information to explain points eg 'seismic reflection surveying', 'biostratigraphy' or 'short-term and intermediate-term carbon cycles'. Each chapter ends with a summary and references. Only references to figures in the book are included at the back, along with the index. There are numerous diagrams and photographs in the text, with hardly any double pages of just text. The diagrams use clear, easy to distinguish colours. The book assumes the reader has a basic understanding of sedimentary rocks, fossils, sedimentary, geochemistry and Earth processes.

The book is divided into three parts Part 1: Survey of the Cretaceous World - which covers paleogeography; fluctuations in sea level; climate and biota. Part 2: The Workings of the Cretaceous World – about biogeochemical changes; volcanic input; geological carbon sinks and the Lost World rediscovered. Part 3: The End of an Era – which is about the Cretaceous mass extinction; seeking an explanation and the effects of the Chicxulub impact.

The preface states the book is "primarily intended as an explanation in Earth System Science viewed through the exotic perspective of the Cretaceous World" to see if the Cretaceous "can provide insights to the variability of the feedbacks that govern the overall behaviour of the Earth system." By looking at the Cretaceous when the climate was warmer, can we answer the growing concern about the impact man has on the planet? The book is very informative about the Cretaceous but I am not sure it answers questions about the Earth's future. The book does not include dinosaurs but even though the planet survived the extreme greenhouse climate, there were still mass extinctions which mammals survived – but will they next time?

Each chapter deals with a different topic. We know where continents were in the Cretaceous but how flat or hilly were they? This is vital to determine the climatic bands. There is a very detailed chapter on paleobotany with clear explanations of modern plants and comparison with fossil ones. Chapter 6, biochemical changes, has no pictures (probably because the subject does not lend itself to photos) fewer diagrams and is more 'text book'. Part 3 starts with the effects phytoplankton had, those who consumed them are mostly extinct, whilst bottom and detritus feeders survived. The last three chapters are about the impact crater. It's worrying that extinctions occurred with just one meteor and fairly low temperature changes! Just one little fault I found, fig 4.53 has 'numbered' red dots but only one dot is actually numbered.

In the Epilogue Peter W Skelton states, "one might hope that past conditions on the Earth when already in a greenhouse state, ……. might give us some clues as to the likely consequences of global warming today. To some extent this may be true." Would I recommend buying this book? Yes, it is a readable comprehensive book about the Cretaceous.

Wendy Hamilton BSc Hons, BA Hons (Open)

Flood and megaflood processes and deposits: recent and ancient examples, I Peter Martini, Victor R Baker and Guillermina Garzón (eds), 2002, Published Blackwell Scientific, Special publication number 32, International Association of Sedimentologists, 312pp, £55 (paperback) ISBN 0632064048.

A fascinating record of 17 papers published after the International Sedimentological Congress in Spain in 1998. The aim of which, was to enhance understanding of large floods, and the impact they have on the Earth's surface. Firstly, it reviews what constitutes a 'megaflood', and why the uniformitarian principle finds it difficult to explain such catastrophic episodes; then analyses the effects in fluvioglacial settings, with emphasis on the deposits, erosion features, and their impact on human activities.

It is divided into five main sections; first giving a background to megafloods, and starting with a perspective paper, explaining high energy megafloods, their palaeohydraulics, climatic influences, and the sedimentary processes involved, from north America to the Martian surface. This is coupled with two further papers dealing primarily with the sedimentary record.

The following four papers concern glacial outwash floods; the first three are a stimulating, but terrifying account of the November 1996 jökulhlaup in southern Iceland. These three papers are contrasted with a final paper documenting an event in 1994 on the mid-Canterbury plains in South Island, New Zealand, in which the authors make interesting comparisons with ancient deposits from the late Pleistocene.

The middle section relates to alluvial fan floods and their outburst implications, using recent case studies in California and Italy. Facies analysis can be utilized to flag up fans, which may be prone to catastrophic outburst. It is difficult to differentiate fan deposits driven by meteorological effects, from those of natural dammed catchment outbursts; research is needed in 'alpine' or glaciated terrains, because of possible human impact.

The penultimate section ranges widely over the topic of alluvial valley floods and possible monitoring methods including the use of aerial photography and remote sensing. An example close to home, and of considerable relevance, is given in a paper about the effects of floods in the Netherlands. Although smaller scale events, they are very important to intensively populated areas, where changes in sedimentation, and soil erosion patterns, can be linked to evolving industrial and agricultural practice.

The final section consists of two 'special cases', both relating to Quaternary glaciation, where the expected amount of sediment is not traceable, a couple of superb 'detective stories' to finish the collection, and possibly act as additional interest to post-S369 Great Ice Age survivors! It is a worthwhile read for anyone interested in catastrophe in the geological record, the environment and its management and hazards, or the world around them.

Diana M Smith BA(Open), BSc(Hons),
Tutor of S260, S269 and S369

Geological Aspects of the Lyme Regis Coast Protection Scheme

Geoff Davis, West Dorset District Council

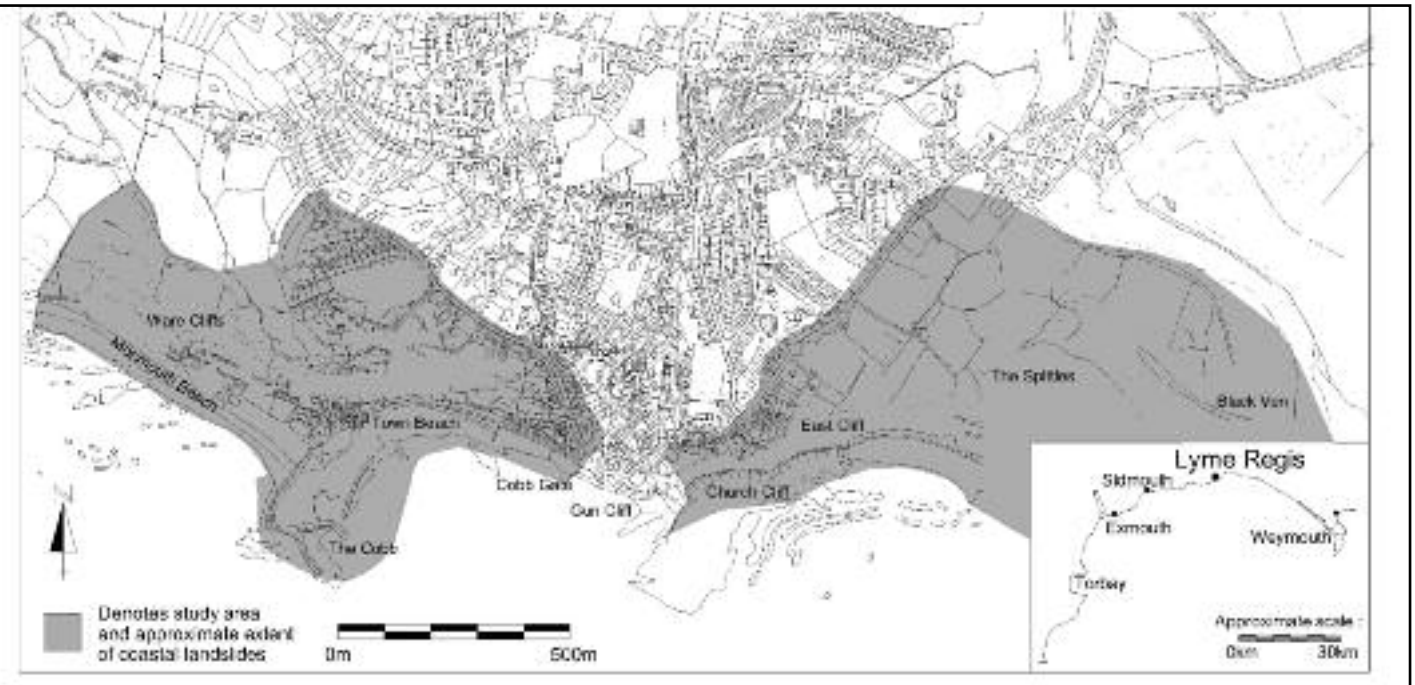

Figure 1. Location plan.

Figure 2. Lyme Regis from the south-west.

Lyme Regis is a popular holiday town in West Dorset, favoured for its beautiful coastal scenery and fossil-rich cliffs (Figures 1& 2). It is also located in one of the most unstable geological settings in the UK. The cliffs on either side of the town are actively retreating inland through marine erosion and associated landslipping. Where unprotected by coast defence structures the rate of erosion of the toe of the cliff is typically around 0.5m per year. The harbour wall, known as the Cobb, is the oldest working breakwater of its type in the country, the original structure dating back at least to the 13th century. However, the other coastal defences in the town are much younger, for example the main seawall along the main frontage was completed in 1860 and the seawall protecting the eastern part of the town was only constructed in the 1950s. Prior to the seawalls, the town's frontage would have been actively retreating inland through marine erosion and landsliding in a similar way to the unprotected coast on either side of the town today.

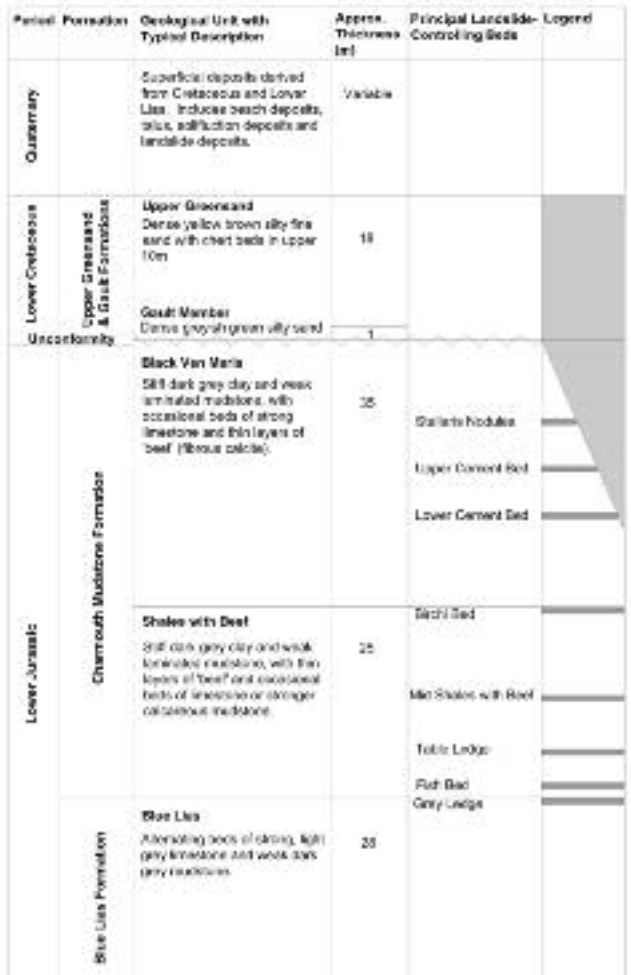
Period
Formation
Geological Unit with Typical Description
Approx. Thickness (m)
Principal Landslide-Controlling Beds
Legend
Quaternary
Superficial deposits derived from Cretaceous and Lower Lias. Includes beach deposits, talus, solifluction deposits and landslide deposits.
Variable
Lower Cretaceous
Upper Greensand & Gault Formations
Upper Greensand
Dense yellow brown silty fine sand with chert beds in upper 10m
10
Gault Member
Dense grey/dark green silty sand
1
Unconformity
Lower Jurassic
Charmouth Mudstone Formation
Black Ven Marls
Stiff dark grey clay and weak laminated mudstone with occasional beds of strong limestone and thin layers of 'beef' (fibrous calcite).
35
Shales with Beef
Stiff dark grey clay and weak laminated mudstone, with thin layers of 'beef' and occasional beds of limestone or stronger calcareous mudstone.
25
Blue Lias Formation
Blue Lias
Alternating beds of strong, light grey limestone and weak dark grey mudstone.
20
Shallots Nodules
Upper Cement Bed
Lower Cement Bed
Birch Bed
Mid Shales with Beef
Table Ledge
Fish Bed
Grey Ledge

Figure 3. Summary of the stratigraphy in the urban area of Lyme Regis, with the principal landslide-controlling beds.

Figure 4. The eastern flank of Lyme Regis from the air. Note the steep sea-cliff in the Blue Lias and the amount of recession which has taken place beyond the end of the sea wall. The landslide below the car park, developed in the Shales with Beef, is expanding and threatening the nearby houses.

Figure 5. The Spittles landslide system, showing large scale landslipping in the Charmouth Mudstone Formation and in the Upper Greensand above. This landslide system is expanding westwards towards Lyme Regis.

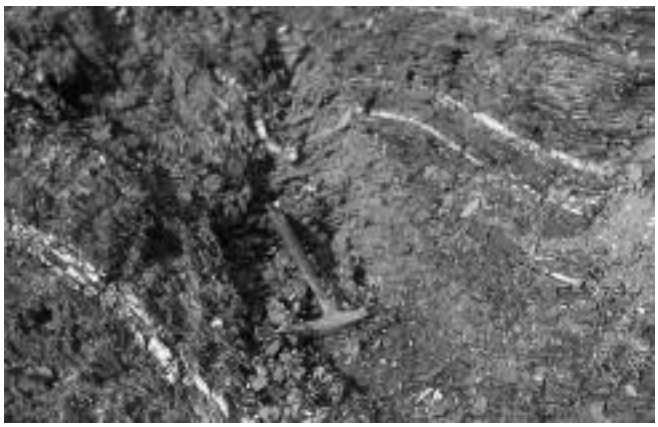

Figure 6. Distorted lamination in the Shales with Beef, due to periglacial disturbance.

Geology and landslipping

The geology of this part of the coast (Figure 3) may be seen in the magnificent exposures in the coastal cliffs. At the lowest level there is the Blue Lias, which comprises alternating beds of strong limestone and weak mudstone. This forms near-vertical cliffs which are retreating through the erosive action of the sea, but they are not prone to large scale landsliding (Figure 4). Above the Blue Lias there are the clays and mudstones of the Charmouth Mudstone Formation, characterised by large landslips which form above thin beds of strong limestone within the clays and mudstones (Figure 5). The Lias is overlain by the Cretaceous Upper Greensand, with the unconformity itself forming a major landslide shear surface.

The characteristics of some of the landslide deposits at Lyme Regis indicate that they were formed in a climate much colder than at present, in the periglacial conditions which existed periodically in Southern England during the Quaternary. The products of periglaciation at Lyme Regis include areas of ground weakened by frost action to over 8m below ground level (Figure 6), sheets of solifluction debris produced by freeze-thaw action and landslides and other forms of mass movement deposits formed as a result of softening of clay in thawing ice-rich ground. Essentially, the effects of frozen ground and associated high groundwater pressures during the Quaternary have left a legacy of ancient mass movement deposits, disturbed ground and shear surfaces which are prone to reactivation in present-day landsliding (Figure7)

As might be expected in an area of coastal erosion with landslide-prone strata, Lyme Regis faces serious instability problems (Figure 8). Historians believe that the original mediaeval town extended a considerable distance into what is now the sea and a large part has already been lost to coastal erosion and landslipping. Over the past 100 years in particular, even with the seawalls and other coastal defences in place, many properties have been destroyed or severely damaged due to landslide movements and there has been considerable disruption to infrastructure, including the loss of the main coastal road in the 1920s.

Investigations

One of West Dorset District Council's principal initial objectives in managing the coastal instability in Lyme Regis has been to gain an understanding of the nature of the instability problem itself. To achieve this, West Dorset District Council and its consultants have carried out a series of multidisciplinary studies involving a considerable investment in acquiring and interpreting data on geology, ground stability, coastal erosion and related issues (Brunsden 2002, Clark *et al*., 2000, Cole *et al.* 2002). Elements of these studies have included:

- historical research
- geological and geomorphological mapping
- borehole and trial pit investigations
- natural gamma radiation logging of boreholes to confirm stratigraphy
- the monitoring of slope movements and groundwater levels
- seabed surveys and sediment budget analysis
- interpretation of the instability affecting the town in terms of the evolution of the coast, both in the long-term and short-term, and the prediction of future landslide behaviour.

Figure 7. Solifluction deposits derived from Upper Greensand being reactivated in recent landslipping.

Figure 8. Examples of effects of landsliding at Lyme Regis.

Figure 9. Part of the Black Ven landslide system, showing several stratigraphically-controlled landslide benches. The geology beneath the urban area of Lyme Regis is similar.

Findings and implications

The principal, and worrying, findings of the investigations may be summarised as follows:

- Much of Lyme Regis has been constructed on ancient landslide systems which extend hundreds of metres inland from the high water mark and consist of numerous interrelated elements.
- Stratigraphy and geological structure exert a strong control on the landsliding. The basal shear surfaces of the principal landslide units occur above particular marker beds within the Lias, which gives rise to typical bench scarp morphology (Figure 9). The Lias strata often have a gentle seaward dip, facilitating the seaward movement of landslide blocks. The presence of faults also has a controlling influence on the location of landslides.
- Stability analyses indicate that many of the landslides are close to failure and ground instrumentation has confirmed continuing widespread movement over most parts of the landslide systems.
- The eastern part of Lyme Regis is under threat from the continuing long-term westwards expansion of the Spittles/Black Ven landslide system.
- The beaches are in long-term decline and are now a small fraction of their original volume, such that they provide little protection to the frontage from wave impact during storms. The decline is considered to be part of a natural process of fragmentation of the beaches along the West Dorset coastline, which has been exacerbated and complicated by the building of structures such as the Cobb and seawalls.
- There is no longer any significant natural supply of beach-forming shingle to the town, due to the activity of large landslips to the west, in Devon, which have interrupted longshore transport.
- There has been a gradual long-term deterioration in the condition of the existing coast protection structures, which are now undermined at their foundations in several locations due to the effects of foreshore lowering. The East Cliff seawall is being out-flanked by marine erosion at its eastern end.
- Continuing coastal erosion represents a potential triggering mechanism for further landsliding. The second principal triggering mechanism is considered to be high groundwater levels, which for many locations are related to rainfall.
- The local climate in West Dorset appears to be becoming wetter, with every one of the ten years from 1993 and 2002 being wetter than the long-term (1868 - 2002) average. This may account for the particularly high incidence of damaging landslide events in West Dorset in recent years. Groundwater levels are not helped by the poor condition of the existing surface water and foul sewers, which have been damaged by many years of ongoing ground movement.

Stabilisation Works

In the 'do-nothing' coastal management scenario, the future of Lyme Regis would appear bleak. There is no reason why the historical prevalence of landslide disasters should not continue, and the predicted continuation of current climate changes, together with the deterioration of the existing coast protection systems, suggests that the situation could become substantially worse in

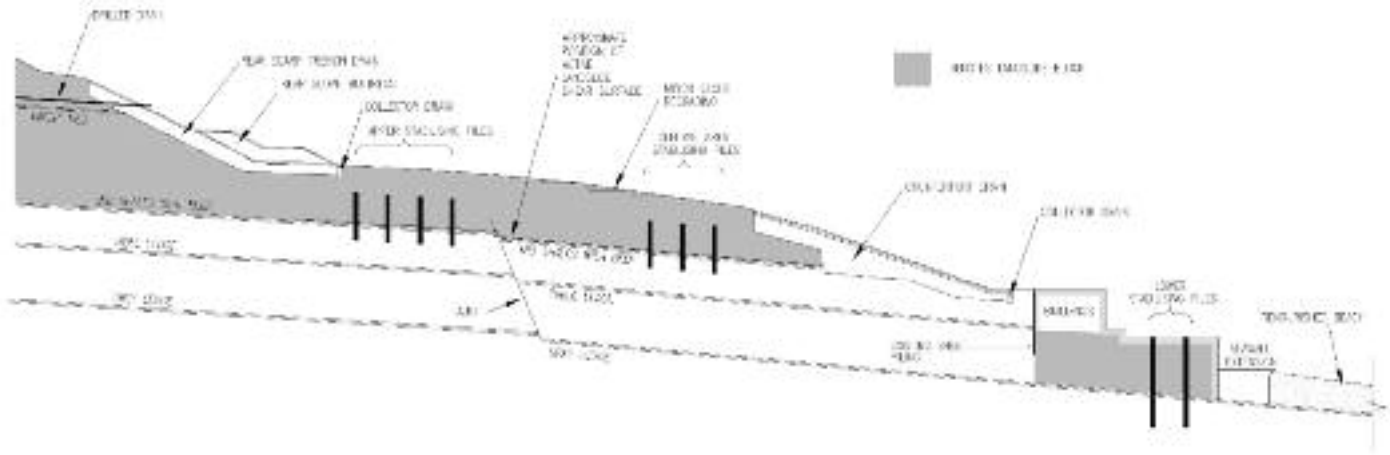

Figure 10. Schematic section indicating the main types of slope stabilisation measure.

the relatively near future. The level of threat is such that West Dorset District Council considers that the only realistic management option to secure the future of the town in the long term is the implementation of coast protection and slope stabilisation works on a large scale.

Such works will comprise several different types of foreshore protection and slope stabilisation measures, in order to deal with the relatively complex landslide systems (Figure 10). These will include:

- beach replenishment, as a first line of defence against the erosive action of the sea
- new seawalls and foreshore structures, in order to hold the replenished beach in position and to provide toe support to the unstable slope behind
- slope strengthening using bored piles and soil nails, to lock unstable landslide units to stable strata below
- drainage systems of different types, to reduce groundwater levels and the risk of landslides being triggered during wet weather.

Figure 11. Bored piles being installed as part of urgent advanced stabilisation works.

The design and construction of the various elements of the stablisation works depends, fundamentally, on a detailed knowledge of the geology and groundwater regime. For example, the levels of individual landslide-controlling strata need to be known to within a few hundreds of millimetres in critical areas, so that the stabilising structures such as bored piles or drains may be constructed deep enough to penetrate the landslide shear surface and to provide a sufficient restraining force to the landslide. The location of faults, even those with small throws, is critical, as an unexpected change in the level of a particular landslide-controlling stratum could severely compromise the proposed stabilisation measure.

The design of the works needs to be relatively robust, in order to allow for the predicted changes in climate and sea-level rise which may take place over the design life of the schemes. As large and complex engineering schemes of this type generally take several years to implement, there is a risk that destructive landsliding could occur before the works are complete. In order to reduce this risk, West Dorset District Council has carried out a series of smaller-scale advanced stabilisation works, involving piling and drainage, in the most critical areas (Figure 11).

Acknowledgements

In developing the Lyme Regis Coast Protection Scheme, West Dorset District Council has received much assistance from consultants and individual experts, including the geotechnical team from High-Point Rendel, Dr Mark Lee and Professor Denys Brunsden. The particular contribution of Dr Ramues Gallois in the geological fieldwork and interpretation is also gratefully acknowledged.

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The Jurassic Coast – A walk through time. 185 million years in 95 miles of coast

Richard Edmonds, Earth Science Manager, World Heritage Team

The Dorset and East Devon Coast became England's first Natural World Heritage Site in December 2001 after eight years of hard work and consultation by Dorset and Devon County Councils and the Dorset Coast Forum. Inclusion within the World Heritage List is an accolade of international significance but for the uninitiated it is probably quite taxing. Everyone can recognise that the Grand Canyon should be a World Heritage Site because it is so big. But the Dorset and East Devon Coast? Well, the answer lies in understanding the geology and its importance within a global context.

World Heritage recognises the Dorset and East Devon Coast as being of 'Universal Value' as defined by the UNESCO World Heritage Convention. There are clear criteria to qualify for World Heritage Site status and the case for the Dorset and Devon Coast is demonstrable under Criteria I for a Natural World Heritage site:

The Site should be an outstanding example, representing major stages of Earth's history, including the record of life, significant ongoing geological processes in the development of landforms, or significant geomorphic or physiographic features.

In summary, the coast between Exmouth in East Devon and Studland Bay in Dorset represents a near-complete sequence of accessible and well-researched rocks through the entire Mesozoic Period of geological time (centre page colour spread). In addition, the coast contains a number of internationally important fossil localities and displays a superb range of active geomorphological processes.

The site represents a sequence through the Triassic, Jurassic and Cretaceous periods in just 95 miles of coastline. There is nowhere else in the world where such a fine succession can be seen in one place and within an accessible and well-studied area. The overall dip of the rocks is gently eastward and this creates a sequential exposure with the oldest rocks in the west and progressively younger rocks forming the cliffs to the east. Therefore, the Triassic rocks form the red cliffs of East Devon between Exmouth and Seaton. The start of the Jurassic is marked at Lyme Regis with the appearance of dark clays, moving through to the striking sandstones of West Bay and on to the towering cliffs of Portland Limestone on the Isle of Portland. In Purbeck, the sequence is complicated by the Purbeck Monocline, a huge fold that, in places, has tilted the rocks into a near vertical orientation. Here, we start to see a near-complete Cretaceous sequence from White Nothe through Lulworth, Durlston Bay and Old Harry Rocks. There is a further complication in that during the Lower Cretaceous a period of erosion took place and, because the underlying rocks are tilted, the gap in the rock record, the unconformity, is more extreme to the west. In Swanage Bay, the unconformity is very small but in western-most Dorset, all of the Lower Cretaceous and most of the Jurassic have been eroded away, while in East Devon, the Upper Greensand and Chalk lie directly on the Triassic.

There are nine internationally important fossil localities across the site including the Triassic terrestrial fauna of East Devon, the Lower Jurassic of West Dorset, the famous Fossil Forest on Portland and at Lulworth, the Kimmeridge Clay and the Lower Cretaceous Purbeck Beds at Durlston Bay. This coast is the best source of Lower Jurassic marine reptiles, fish and insects anywhere in the world. Furthermore, some of the fossils are renowned for their soft part preservation. The Late Jurassic Fossil Forest is unique of its age and includes soils, tree burrs and the perfect preservation of wood providing a detailed glimpse of climate patterns at the end of the Jurassic. Durlston Bay yields the richest assemblage of Lower Cretaceous reptiles, fish, insects and early mammals known anywhere in the World.

The coast contains numerous examples of active geomorphological processes. The Budleigh Salterton Pebble Beds are composed of highly distinctive quartzite pebbles that can be found on all beaches across the site and beyond. They are truly unique and represent a diagnostic marker that has been used to trace the movement of beach sediments along the English Channel. The spectacular landslides of the East Devon and West Dorset Coast include the Great Bindon Landslide of 1839; probably the first event of this kind recorded in scientific literature. Chesil Beach is a world-renowned feature famous because of the volume, type and size grading of its pebbles. The relationship between the beach, the landslides to the west and changing sea-levels during the last glaciation, is the subject of ongoing research and a new understanding of the dynamic nature of this complex sediment cell during relatively short periods of geological time. The coast of Purbeck is one of the most celebrated cliffed coastlines in the country. The forms range from the spectacular vertical Chalk cliffs, arches and stacks of Ballard Down and Old Harry Rocks to the huge relict landslides of St Aldhelm's Head and White Nothe and the perfection of Lulworth Cove and Durdle Door. This coast is a 'classic' site to demonstrate geological control on coastal evolution with the sea eroding both along and across the grain of the rock strata.

The completeness of the geology, the fossil sites and the geomorphology clearly fulfils the main criteria for a natural World Heritage Site but there are other unique and important aspects to the case. This coast has, and continues to provide vital evidence for the development of the Earth sciences. The history reads like a 'who's who' of geological science and the coast provided valuable evidence to inform the great evolutionary debate. Mary Anning (1700-1746) is perhaps the world's most famous fossil collector while the illustration, Dauria Antiquior, (a more ancient Dorset) by Henry De la Beche was the first-ever attempt to portray a past environment (centre spread Plate 2). Today, important research and fossil discoveries continue to be made on a yearly basis. In October 2001, the first dinosaur trackway from Portland was discovered and represents some of the earliest prints of this age seen in the Purbeck Beds of southern England. The coast is clearly of huge educational importance and offers a section through an entire sedimentary basin with the associated Wytch Farm Oilfield, an invaluable resource for petroleum geology. Finally, the landscape owes its variety and great beauty to the diversity of the underlying geology.

Conservation and management

The site extends from the low-tide mark to the top of the cliffs between Exmouth and Studland Bay but excludes the developed frontages of the 'Gateway towns' along this coast. The cliffs and

foreshore lie entirely within existing Sites of Special Scientific Interest as identified by English Nature and conservation of the World Heritage Site will continue to be administered through the SSSI designation. Most of the hinterland lies within three Areas of Outstanding Natural Beauty and protection to the setting of the site will be managed through these designations. What World Heritage brings to the coast is an international recognition of its importance and a wider partnership in its management and responsible use.

A World Heritage team has been established with a Steering Group made up from a broad range of interest groups. There is a clear and wide-ranging Management Plan that sets out the tasks for both a Science and Conservation Advisory Group (SCAG) and a Tourism Working Group. The former will be composed of a small group of organisations with responsibility for, or a direct interest in, the site, supported by a wider network of experts. An example of the type of management envisaged for the conservation of the site is the West Dorset Fossil Collecting Code of Conduct. The Code seeks to balance the wide range of interests along this particularly fossil rich section of the site. It recognises the role of collecting and the requirements for site management and research. There is a Register of Key Scientifically Important Fossils held at the Charmouth Heritage Coast Centre, accessible through their web site at www.charmouth.org. The web site has the facility to register areas of research interest while individuals can also sign up to receive e-mails each time a new specimen is recorded. One of the remaining challenges is to promote acquisition of important fossils to museum collections in the UK and this is an area of work currently being explored. At the time of writing, the SCAG has yet to meet but one of the early tasks will be to set an agenda for work in the future, relating to conservation of the interest, research, appropriate use and higher education.

Educational use and enjoyment of the site

UNESCO recognises the importance of promoting awareness and understanding of World Heritage Sites and the designation offers a 'shop window' for the Earth sciences within the UK. Not that this is not already the case: one example is fossil collecting, a highly popular activity around Charmouth and Lyme Regis. The Charmouth Heritage Coast Centre was established in 1985 to promote safe and responsible collecting along this part of the coast. Luckily, the erosion rates are high and millions of fossils are washed onto the beaches each year, creating an ideal opportunity to inspire people about our fascinating ancient past.

Indeed, this coast, and the story that it contains over 185 million years of time, gives rise to a wide range of diverse interests. The changing geological story runs from ancient Triassic deserts through a tropical sea packed with marine life to the Fossil Forest and dinosaur-infested swamps. The geology also links the coast together and gives rise to associated interests. East Devon and Purbeck are spectacular places to appreciate how the underlying geology influences the landscape and wildlife habitats. Purbeck, Portland and Beer Stone (East Devon) are three famous building stones and a knowledge of their use across the country in cathedrals and other important buildings is fundamental to understanding our stone heritage. Beer Quarry Caves is a big surprise, in more ways than one (www.beerquarrycaves.fsnet.co.uk). Portland is an exceptional place and the quarried landscape contains a wealth of interest from the geology to industrial and cultural heritage, wildlife and the arts. Tout Quarry, near the top of the island contains a unique blend of these interests, including modern sculpture, through the work of the Portland Sculpture Trust (www.learningstone.com).

Importantly, many of these interests are best explored out of season and here lies a key objective of the World Heritage Team; to promote enjoyment and understanding through appropriate activities that do not damage the interest while also delivering economic benefit to the local economy. Tourism is important to Dorset but in the holiday season the area is busy. World Heritage will be used to help people who already come to the coast to learn about and enjoy it further but also to promote out-of-season and special-interest tourism. Short breaks, guided walks and events marketed to specific audiences are seen as the tools to deliver this tourism, working with a wide range of organisations including heritage centres, museums, the local geological community, boatmen and individuals.

The development of the World Heritage Site is through consensus within a wide range of interest groups along the length of the site and beyond. A Steering Group governs the work and the detail is developed through a Science and Conservation Advisory group, Education Working Group and Tourism Working Group. A World Heritage Trust has been established with the aim of promoting conservation and educational initiatives. Publications and other fundraising initiatives will support this work across the site. A series of strategies have been prepared relating to economic regeneration, interpretation and marketing. The approach of the World Heritage Team is to develop local initiatives through a site-wide strategic framework, working with local communities to drive up quality and create opportunities to promote educational initiatives and out-of-season, special-interest tourism.

The World Heritage Team recognises and thanks the invaluable contribution of so many researchers and the letters of support while building the nomination for World Heritage Site status. We hope to use this accolade to promote conservation, research and understanding of the site, together, as a window into the Earth sciences.

Book reviews

Changing Sea Levels by David Pugh, 2004, Cambridge University Press, 265pp, £30.00, ISBN 0521825326 (hardback) 0521532183 (paperback).

The subtitle gives the scope and the limitations of this textbook: "Effects of Tides, Weather and Climate". There is virtually nothing about the very long term effects of plate tectonics changing ocean basins, let alone about sequence stratigraphy! But within its limits it has a great deal of information presented in a clear and readable way. It could be useful to students of S330, Oceanography, for supplementary material. It is perhaps designed more for geography- than geology-oriented courses. There are self assessment questions at the end of each chapter. The chapter on extreme sea levels, flooding risks, and possible responses has a very useful survey of this crucial area. There is a helpful glossary, and the figures and tables are clearly drawn. Illustrative examples are drawn from around the world, but with a good proportion from Britain. Periodic boxes treat interesting topics: "Flood warning systems", "A tidal power scheme", "Misleading short term trends" – perhaps there should have been an index of these. The bibliography is not overwhelming, but finds room for some choice items: "On the tides at the Port of London" 1836, "The case of Venice" 1991, "Scientists and the Sea, 1650-1900", 1997.

Philip Clark, BSc Hons (Open)

The Geology of Spain, Gibbons, W. and Moreno, T. (eds) 2002 The Geological Society, 632pp £27.50 paperback, £85.00 hardback, ISBN 1862391270 (pb) 1862391106 (hb)

… so good I bought it twice!

On a Barcelona family holiday in 1966 I rapidly became bored with the beach and desperately wanted to explore inland… particularly the geology… but it wasn't to be. I had to wait until 1996 when Bill Gaskarth's OUGS trip to the Pyrenees introduced me to the country's geology – and what a feast that was as we explored Palaeozoic to Mesozoic rocks deformed by the Alpine orogeny!

Appetite whetted I've since been to the Picos de Europa – fleetingly – it is on the "go back there" list, spent a day in the central ranges north of Madrid where we saw beautiful metamorphic rocks and had a run in with the police for stopping on the hard shoulder of a motorway – "it's a very old motorway – no one uses it very much", said our guide. Then Tenerife, Lanzarote, Almeria, and I'm now getting to know the rest of Andalucia.

But… a big problem has been the dearth of comprehensive literature – preferably in English. Gibbons and Moreno of Cardiff University have filled this gap very adequately by editing an A4, 649pp book that provides a detailed summary, including the Canaries and Balearics. Written by seven *pages* of contributing authors and refereed by almost 50 (mainly UK and Spanish) geologists, the book takes you on a chronological journey through Spain's geology plus sections on Alpine tectonics, Cenozoic volcanism, and economic and environmental geology. Chapters begin with an overview and then deal with individual areas, making searching easy.

A colour fold-out map shows the country's main geological divisions and the text is really well illustrated with plenty of excellent figures and photographs: perhaps a favourite of mine, and one which will serve to illustrate the scope of the book is Figure 1.2 *'The geology of Spain is remarkably diverse'*, showing El Teide shield volcano, a mercury mine at Almadén, Miocene foreland basin sediments, an Ordovician trilobite, the 600 m-high cliffs at Cabo Ortegal made up of ultramafic mantle and lower crustal rocks and finally, Alpine folding in the La Olla anticline.

'The Geology of Spain' *isn't* a field guide (my retirement project?!) but it does give really comprehensive coverage of Spain's remarkably varied geology; it is well (40 pp) indexed and meticulously (nearly 100 pp) referenced. If you plan a visit to any part of the country it will certainly help you to make sense of what you are seeing… oh yes – 2 copies? Well, at 1.7kg I baulked at carrying it back and forth between the UK and Andalucia several times a year!

Linda M H Fowler (OU graduate, S260 tutor and staff tutor)

Volcanoes: Second Edition by Peter Francis and Clive Oppenheimer, 2004, Oxford University Press, 521pp, £28.99 paperback ISBN 0199254699

The 1993 book "Volcanoes: A Planetary Perspective" by the late Peter Francis was a 'must' for anyone interested in volcanism. It was reviewed in Journal 16 No 1 in 1995. The book has now been revised and updated by Clive Oppenheimer who was one of Peter's PhD students from 1989-1991. The first edition had a total of 443 pages whereas the second edition runs to 521. The original material has been retained, with minor additions, photographs and maps and with some re-arrangement of text. I particularly like the addition of the list of sections at the beginning of each chapter.

The eighteen chapters range over the origins of volcanism, composition of the planets, plate tectonics, types of volcanic activity, lavas, pyroclastics, super-eruptions, submarine volcanism, extraterrestrial volcanoes, climate change, volcano monitoring and risk reduction. New to this edition are updates on planetary missions to Venus, Mars and Jupiter and coverage of major eruptions since the first edition was written, including Montserrat. There are excellent new chapters on volcano monitoring and reducing volcanic risks. The style throughout is easy to read and the diagrams and black and white photographs are excellent. Many of the chapters do not require any previous geological knowledge: particularly fascinating are the descriptions of the classic eruptions of Vesuvius, Krakatau, Mt Pelée and Mount St Helens and the chapter on Eruptions and Climate which includes a section on the effects of some great historical eruptions: Krakatau 1883, Tambora 1815 and Mt Pinatubo 1991. At the end of each chapter are details of Further Research and a comprehensive list of References.

In the Preface to the first edition Peter Francis wrote: "... the kind of book that I take most pleasure in writing is the sort I would enjoy reading; a book to be read rather than consulted. If this book fills its intended purpose, it will end up bedraggled in bathrooms or dog-eared in hotel bedrooms, rather than primly pristine on a shelf." In the Preface to this second edition Dr Oppenheimer says "I realized that it would be a tall order to select the proper balance of new material, and impossible for me to match Peter's skill in communicating with such clarity, humour, and scientific rigour. Nevertheless, great strides have been achieved in volcanology in the past decade, and many new developments needed to be conveyed in order to keep the text in use."

In my opinion Dr Oppenheimer has combined the original work with new material to produce a superb book which is a pleasure to read and at a modest price it should be on the book list of everyone interested in volcanology.

Elizabeth Maddocks BA (Open)

Principles of Stratigraphy by Michael E Brookfield, 2004, Blackwell Publishing Ltd, 340pp, £27.99, (paperback) ISBN 140511164X.

In his preface, the author states that he wrote Principles of Stratigraphy in order to 're-establish the necessity for tectonic and geophysical knowledge to interpret the stratigraphic record'. This book, therefore, covers much more than the basics of stratigraphy - how to classify and correlate strata on the basis of their lithological and palaeontological characteristics. It reviews most aspects of the Earth sciences that are necessary to reconstruct segments of Earth history from the rock record. The book is profusely illustrated with line diagrams, and four sides of colour diagrams. There are many black and white photographs which are poorly reproduced. A preliminary scan of the book revealed that most of the diagrams are copied directly from other books and research papers. I find this practice a pretty reliable indicator that a book is likely to be rather dry and dense, though broad in its coverage. Later reading proved my first impression to be correct.

Principles of Stratigraphy is divided into three parts. Part 1 Basics is a basic, if rather dense, guide to sedimentology in 100 pages. It covers weathering, sediments and sedimentary rocks, and major environments and their recognition. To follow this material readers will certainly need to have the OU second level Geology course under their belts, which is not surprising as the author states that the book is intended for second year undergraduates. Nonetheless the treatment here is too dense for this part of the book to be recommended as second year course text in sedimentology. However, this opening part of the book does establish that stratigraphy is about tracing environments in space and time, which is the title of Part 2.

Part 2 deals with the basic nuts and bolts of stratigraphy. Rather than deal with these under the usual headings of lithostratigraphy, biostratigraphy, and chronostratigraphy, the author examines in turn the vertical, horizontal (largely about correlation and mapping) and time dimensions. This treatment is followed by 26 pages on basin analysis and stratigraphic systems (including sequence stratigraphy).

Part 3 Interpreting geologic history has chapters dealing with tectonics, sealevel changes, climate, biology, stratigraphic problem times and places (Archean, Proterozoic, Quaternary, and archaeological stratigraphy), and extraterrestrial stratigraphy (Moon, Mercury, Mars, Venus). For OU graduates the 114 pages of this part will provide a good read, bringing together under the banner of stratigraphy many topics covered in some second level and all third level Earth science courses. But as this material comprises only one third of the tome, it would be an interesting book to borrow rather than to buy.

Chris Wilson OUGS President